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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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« CONTENTS »

Thickness of strata ..... *Vincent C. Kelley* 289
Sediment distribution in the southern oceans around Antarctica ..... *Jack L. Hough* 301
Examples of probable lithified beachrock ..... *William F. Tanner* 307
The Curley limestone—an unusual biostrome in central Utah ..... *Paul Dean Proctor and David L. Clark* 313
Multivariate analysis of mineralogic, lithologic, and chemical composition of rock bodies ..... *W. C. Krumbein and John W. Tukey* 322
Sandy zones in the Chattanooga of the Eastern Highland Rim, Tennessee ..... *Stuart W. Maher* 338
Sedimentary structures in the Upper Carboniferous of north and central Derbyshire, England ..... *John Trevor Greensmith* 343
Heavy-mineral suites in unconsolidated Paleocene and younger sands, western Tennessee ..... *Reginald R. Blankenship* 356
Clay mineral composition of Recent sediments from Sigsbee Deep ..... *Haydn H. Murray and Jack L. Harrison* 363

DISCUSSION

Fucoidal markings in The Swan Peak formation, southeastern Idaho ..... *Clyde T. Hardy* 369

ERRATA

A new method of expressing particle sphericity ..... *Bert C. Aschenbrenner* 370

INDEX 371

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Sedimentary structures in the Upper Carboniferous of north and central Derbyshire, England ..... *John Trevor Greensmith* 343
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Clay mineral composition of Recent sediments from Sigsbee Deep ..... *Haydn H. Murray and Jack L. Harrison* 363
DISCUSSION
Fucoidal markings in The Swan Peak formation, southeastern Idaho ..... *Clyde T. Hardy* 369
ERRATA
A new method of expressing particle sphericity ..... *Bert C. Aschenbrenner* 370
INDEX 371

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Brazos river bar: a study in the significance of grain size parameters. By Robert L. Folk and William C. Ward

Mineralogy of some Pennsylvanian carbonate rocks of Illinois. By Raymond Siever and Herbert D. Glass

A fabric and petrologic study of the Pleasantview sandstone. By Gene A. Rusnak

Mineral alteration in rocks of Middle Eocene age, Absaroka Range, Wyoming. By Richard L. Hay

Differentiation of marine and sub-aerial sedimentary environments by volume percentage of heavy minerals, Mustang Island, Texas. By John S. Bradley

Sediments of three bays of Baja California: Sebastian Viscaino, San Cristobal, and Todos Santos. By K. O. Emery, D. S. Gorsline, E. Uchupi, and R. D. Terry

Heavy mineral studies in tills of Ontario and adjacent areas. By A. Dreimanis, G. H. Reavely, R. J. B. Cook, K. S. Knox, and F. J. Moretti

Differential compaction of Pennsylvanian sediments in relation to sand-shale ratios, Jefferson County, Illinois. By Joseph C. Mueller and Harold R. Wanless.

Beach erosion and concentration of heavy mineral sands. By C. Borreswara Rao.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 4, PP. 289–300
FIGS. 1–4, DECEMBER, 1956

THICKNESS OF STRATA

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University of New Mexico, Albuquerque, New Mexico

ABSTRACT

"Thick" and "thin" applied to bedding are terms that are relative to one's stratigraphic training and experience and relative to the associated strata. The terms, "thick bedded," "medium bedded," and "thin bedded" should not be used without definition, although undefined usage is common in the current literature. Recent efforts to standardize the limits of "thick," "medium," and "thin" for bedding are in considerable disagreement.

Standardization or pigeon-holing of thicknesses may be necessary only for statistical treatment of stratification. However, in such studies mean bed thickness, thickness frequencies, and other statistical indices may serve to better describe and understand the origin of the assemblage. Many formations possess stratification facies (phyllofacies) as well as biofacies, and lithofacies. It may be just as productive to determine regionally the stratification indices or ratios as it is to study sand-shale ratios. It may be possible and useful to construct regional iso-stratification (isobed) maps just as it is to construct isolith maps.

It is proposed that the beddedness of sedimentary units be expressed by the following index.

$$\text{Stratification index} = \frac{\text{no. of beds} \times 100}{\text{thickness}}$$

The task of determining, measuring, and counting individual beds is large and subjective. However, it may consist of a partial sampling just as sampling for lithology or chemical composition commonly is. I am convinced from my consideration of the quantitative and statistical approach to bed thickness that the additional effort involved yields a much better awareness and appreciation of the nature and significance of bedding than without such an approach.

Recently several papers have appeared in the geologic literature proposing that the thicknesses of strata be pigeonholed and that standard limits be assigned for relative terms such as thick and thin. For quantitative and statistical treatments of stratification it appears desirable and necessary that some sort of pigeon-holding of thicknesses be established. However, the advisability of standardizing the meanings of such general terms as bed and lamina or such relative terms as thick and thin is questionable.

Bedding and stratification, as well as beds and strata, are well established terms that are mutually synonymous, and it is illogical to try to assign a quantitative meaning to beds and not to strata. Both *bed* and *stratum* have been defined as a single layer bounded by bedding planes or surfaces or abrupt changes in lithology. Yet both of these terms have been used collectively for sets of beds or intervals within which there are less marked or less significant surfaces of stratification and lithologic changes (Grabau, 1913, pp. 698–700). Although it would appear that such usage should be avoided, there are practicalities which may make it desirable to use the terms in a collective sense sometimes.

Efforts to standardize bed thickness terms may have started with Twenhofel's rather casual statements (1932, p. 603) "that although the upper limit of a lamina is indefinite it may be placed at about one-half inch." Also he stated that "a stratum may be stratified" and if the stratum contains thin beds they are "known as laminae or laminations" whereas the thicker units of the "stratum" he termed "stratum layers." Later in a critical study of stratification in beaches, bars, and dunes Thompson (1937, p. 726) used the term laminae for layers as much as 1.2 inches thick. About the same time Otto (1938, p. 575) in connection with lithologic sampling and in

consideration of the nature of his "sedimentation unit" stated that "a lamina is the smallest recognizable unit layer of particles of a sediment. The thickness of a lamina may vary from microscopic size for clays to many inches for coarse gravel deposits."

Otto's concept corresponds closely with the early statement by Geikie (1903, p. 860) that "the smallest subdivisions of the Geological Record are laminae, a number of which may make a stratum, seam, or bed." A lamina is perhaps more a matter of form rather than of thickness. A leaf ground to a powder is no longer scalelike; laminated refers to a form characterized by multiple parts each of which is characterized by two long axes and one short. Beds are laminae because of their lateral extent with reference to their thickness and their grouping with similar forms. If one could suspend the original Main Reef conglomerate group or one of its beds and view it in its entirety, it might best be referred to as filmy or laminated, yet each of the component units is commonly several feet thick. In 1939 Twenhofel (p. 494) suggested an upper limit for laminae at 1 cm. (0.39 inch) and since then Payne (1942, p. 1724) followed by Shrock (1948, p. 5), Pettijohn (1949, p. 121), Krumbein and Sloss (1951, p. 97) and others have conformed to this usage.[1]

Although laminae generally have been considered only a special category of stratification, Payne (1942, p. 1724) defined a stratum "as a layer, greater than 1 cm in thickness. . . ." Payne's remarks have been adopted rather generally by the principal reference and textbooks on sedimentary rocks. Therefore, it is pertinent, in view of the very recent (Ingram, 1954, p. 938) definitions of parting in connection with stratification, to note that Payne (1942, p. 1724) defined the term parting as "a lamina occurring between massive strata different in lithology from the parting itself." This is very near to the much used term "shale break." The meaning for parting suggested by McKee and Weir (1953, p. 384), Ingram (1954, p. 938), and Gray (1955, p. 147) are in the same sense as mineral parting, rock cleavage, fissility, or shaliness. "Fissility," "shaly," or "laminated" are perhaps adequate, and it is confusing to introduce the term parting in the sense of fissility in view of the common usage of parting in stratigraphy as defined above by Payne.

Payne, in contrast to his simple definition (above) of a stratum, defined a bed as "a unit of sedimentary rock, of lower than member or formation rank, composed of two or more *strata* or *laminae* (italics added) that manifest some degree of lithologic unity," the components of which might be of the same or related types. Although this definition is satisfactory in itself, it may be deduced from it that some beds are laminae, as for example, three lamina whose total thickness is less than 1 cm. In 1953 McKee and Weir (p. 382) simply reversed the suggestions of Payne and proposed that the term stratum apply to any sedimentary layer and that the term bed (p. 384) be used only for those layers greater than 1 cm. By their proposals beds and laminae are subdivisions of strata and hence stratification and bedding would no longer be mutually synonymous.

The separation of sedimentary layers into laminae and beds or strata involves only two divisions of thickness. Several more have been proposed, and from the point of view of sedimentology and the analyses of the significance of bed thickness there is no evidence yet assembled that the division at 1 cm is more important than at 1 inch or 1 foot. Several workers for a decade or more have subdivided beds into "thin," "medium," or

[1] Geikie (1903, p. 634) early stated that "Laminae are the thinnest paper-like layers in the planes of deposit of a stratified rock." Paper is generally much thinner than 1 cm; furthermore "laminae" is used for sheeting or fissility in slate, schist, and flow layers and therefore the stratigrapher should take care in setting thickness limits for the term.

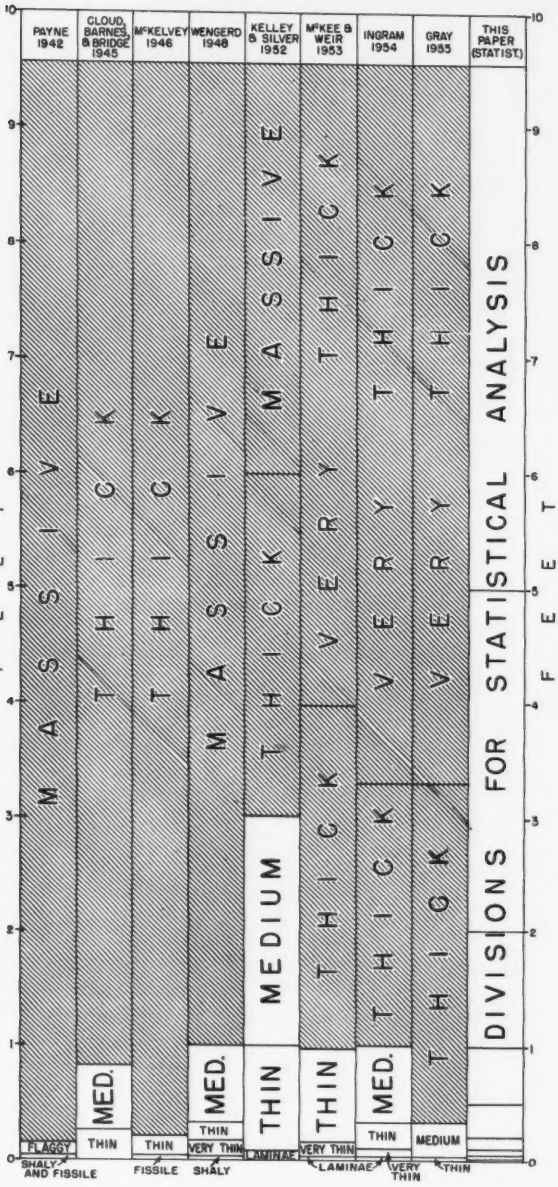

FIG. 1.—Classifications of bed-thickness divisions (arithmetic scale).

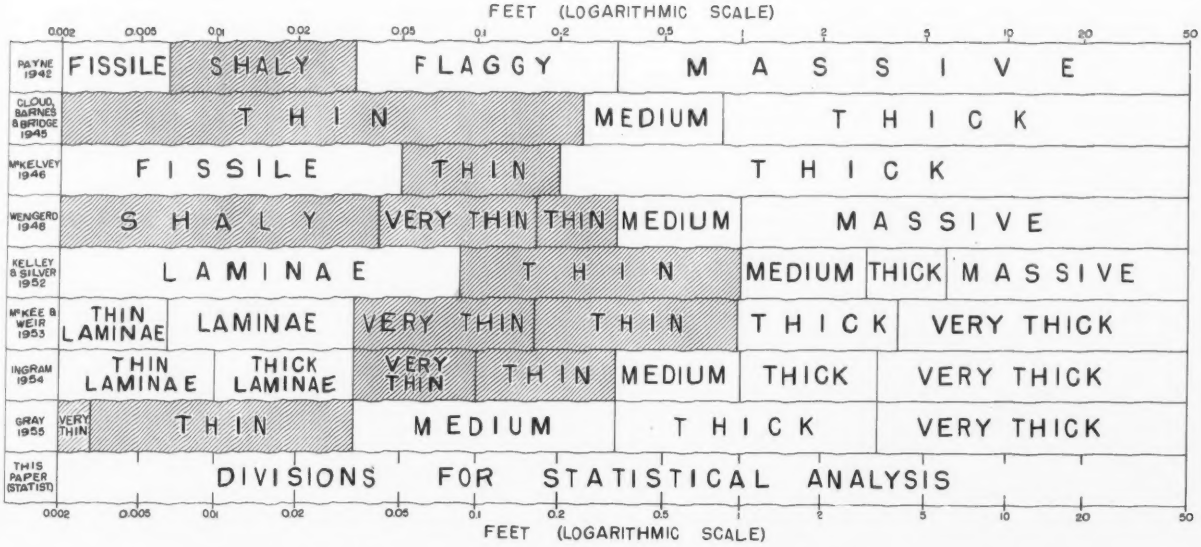

FIG. 2.—Classifications of bed-thickness divisions (logarithmic scale)

"thick" categories and McKee and Weir (1953, pp. 383–384) and Ingram (1954, p. 937) have divided (each in his own way) laminae into thick and thin. Several classifications are shown in figures 1 and 2. The differences between the several proposed divisions are rather considerable. One's impressions of what the limits should be are apt to be colored by training and experience. The terms are meant to be relative—relative to one's experience and relative to the associated beds. Thus, if one has worked dominantly with mudstone or with the Permian Phosphoria formation of Idaho and Wyoming, for example, his (McKelvey, 1946, pls. 1–7) concept of a thick bed is likely to be thinner than it would have been if he had worked dominantly with continental sandstone sequences like the Upper Cretaceous Mesaverde group of the Colorado Plateau or especially the Triassic-Jurassic Glen Canyon group of the same region.

Furthermore, a thick sheet of paper is thinner than a thin board, and what is thick for siltstone may not be thick for sandstone or conglomerate. What is thick for a deltaic sandstone may be thin for a neritic mudstone. These comments, however, are made only to bring out the different points of view that are involved. They are not intended as arguments against standardization of thickness categories, but rather to stress the careful consideration that should be given to the establishment of limits. I do not believe at present that it is necessary or advisable to attach the terms "thin," "medium," or "thick" to the thickness categories. In any event this subject is of importance to so many geologists and as pointed out above so subjective that no one person should propose a standard. If the terms are to be standardized it should only be done by a large committee consisting of men of much experience and varied interests in the subject.

McKelvey[2] (1946, pls. 1–7) proposed that beds as thin as 2½ inches; Ingram (1954, p. 938) as little as 12 inches; and Gray (1955, p. 147) as little as 4 inches be termed "thick." McKee and Weir (1953, p. 383) have termed beds only 50 inches; Ingram, only 42 inches; and Gray, only 39 inches, *very thick*. In my experience these are hardly the concepts that many geologists have of "very thick" beds. In any event the *very thick* category suggested by all the recent writers on the subject embraces too wide a range, i.e., about 40 inches to several hundred feet.

Most of the proposed recent divisions are based on metric measurements although the English equivalents are usually indicated. In a country where we grow up by the inch, travel by the mile, and drill holes by the foot it is neither very practical nor conducive to easy acceptance to set up thickness standards based on the metric system. For most American and English geologists only the millimeter interval is readily used probably because the English system has no similar small unit, but for greater intervals the English mind is too firmly impressed with inches and feet. There are few who would have an immediate mental picture of a bed 278 cm thick. Of course, the same might be said of those educated under the metric system for a bed 9 feet thick. Ingram (1954, pp. 937–938) has proposed " . . . a geometric scale with a starting point of 1 cm and a common ratio of $\sqrt{10}$." These lead, even if rounded off, to some odd English limits such as 1/10 to 2/5 inch (thickly laminated) or 4 to 12 inches (medium bedded). The thick-bedded interval suggested by Gray (1955, p. 147) includes layers from approximately 4 inches to 39 inches (given by him in metric units as 10 cm to 1.0 m). Such intervals, regardless of whether they be considered thick or thin, are neither simple nor easily measured by the English system. Most geologists are equipped with stadia rods, engineers scales, and steel tapes in

[2] It should be noted that McKelvey was probably not making a general proposal, but rather for the phosphatic member of the Phosphoria formation.

English units and it is somewhat laborious and might even be considered pedantic to transform such measurements to the metric system.

The values of thickness assigned to the intervals thin, medium, and thick beds above are too low. I have proposed (Kelley and Silver, 1952, pp. 30–31) and know of others who have used similar limits as follows:

Massive:[3] <6 feet
Thick: 3–6 feet
Medium: 1–3 feet
Thin: 1 in. to 1 foot
Laminae: <1 in.

However, it is not proposed that this be accepted. The usual reason for defining the limits of thick or thin beds is so one might write, for example, "the lower one-third of the Badger formation consists of very thick bedded sandstone" and have the meaning clear, i.e., where "very thick bedded" may have been defined as 4–40 feet. Often the use of such expressions is merely a substitute for careful or detailed collection of thickness data. One might better say where possible that "the beds of the lower one-third of the Badger formation range from 8 to 23 feet in thickness." Very commonly the thickness terms occur in descriptive sections in notation form. Actually there is little reason to use the general term as may be seen from two forms of presentation of a typical item as follows:

(1) SANDSTONE: medium-bedded, buff, fine-grained, subrounded, etc.
(1') SANDSTONE: 14"–2.5', buff, fine-grained, subrounded, etc.

In case some should feel that this is unnecessary instruction, it may be pointed out that almost all the current (since Ingram, 1954) stratigraphic literature contains examples of undefined reference to "medium-bedded" or "thin-bedded" layers.

If the only reason for standardization of thickness intervals is so that others may know what we mean by "medium-bedded" it may as well be left undone for each one could more satisfactorily state his own limits or give the range of thickness. The real reason for setting up standard thickness divisions should lie in the use of the data so assembled for quantitative or statistical studies that may aid in a better understanding of the nature and origin of a particular set or sequence of strata.

Bedding, like clastic sediment, may be subjected to a sort of "mechanical analysis." In addition to measuring a section by "sets" or "units" as is done in the usual descriptive sections one might measure the thickness of each individual bed and tally it opposite thickness intervals or "pigeon-holes." The principal lithologic differences may or may not be set up on separate sheets or lines. The data obtained in this manner may then be shown in histograms or frequency curves for (1) the total lithology or (2) individual lithologies within a bed set, coset (McKee and Weir, 1953, p. 383), member, or formation.

A hypothetical case (Beta formation) is presented below:

[3] For the purists of English grammar who oppose the use of "massive," a bed becomes massive or imposing by its thickness. Most geologists will comment on a "big bed" in a section and big may mean large or massive at least to a liberalist of English grammar. Massive is also used to mean without internal structure (parting or fissility), as in minerals without fibrous, platy, or cleavable structure, or as "the Bedford shale contains two massive sandstones."

DESCRIPTIVE STRATIGRAPHIC SECTION
(Thin-bedded, <1 foot; medium-bedded 1–5 feet; thick-bedded, 5–10 feet)

No.	Description	Thickness (feet)
	Top; Gamma formation above	
18	Mudstone: mostly thin-bedded, dark gray, silty to impalpable	23
17	Limestone: mostly thick-bedded, light gray, much lacey chert	18
16	*Mudstone: mostly thin-bedded, dark gray, silty to impalpable*	12
15	Sandstone: medium-bedded, white to buff, medium-grained, subrounded	10
14	Mudstone and Sandstone: thin- to medium-bedded, mudstone like *no. 16*, sandstone like no. 15	14
13	Limestone: mostly medium-bedded, light gray, etc	17
12	Mudstone and Limestone: like nos. 17 and 16	21
11	Sandstone: medium-bedded, like no. 15	5
10	Limestone: mostly thick-bedded, dark gray, fine-grained, chert nodules and lenses	22
9	Mudstone: like no. 16	6
8	Sandstone: like no. 15	7
7	Mudstone: like *no. 16*	3
6	Limestone: thin- to medium-bedded, dark gray, fine-grained	28
5	Mudstone and Limestone: like no. 12	19
4	*Mudstone and Sandstone: like no. 14*	32
3	Sandstone: mostly medium-bedded, like no. 15	11
2	Limestone: like no. 13	8
1	*Sandstone: medium-bedded, grayish green, coarse-grained, angular*	9
	Total	265

Base; Alpha formation below.

The bedding of the hypothetical Beta formation may be recorded as in table 1. Here the number of beds falling within the thickness intervals is shown opposite each numbered item of the Descriptive Section. Where an item, such as no. 14, consists of two rock types the number of each type or component may be shown. The total number of beds in the Beta formation is 456. The ratio of the thickness of the formation to the total number of beds (265/456 = 0.58) is the average or mean bed thickness of the formation. The reciprocal of this thickness (1.7) is the number of beds per foot. This might also be expressed as 170 beds per hundred feet of section as a sort of *index of the beddedness* of the formation (stratification index).

Further breakdown of the bedding characteristics of the formation is shown in table 2.

The data of table 1 are best illustrated in histograms and cumulative curves as shown in figures 3 and 4. From table 1 and figure 3 it may be determined that 44 percent of the mudstone beds are 0.2–0.5 foot in thickness; 74 percent are 0.2–1.0 foot in thickness; and 96 percent are 0.1–1.0 foot in thickness. Only 47 percent of the number of limestone beds are 0.1–1.0 foot thick. Other similar comparisons may be made and some of these are summarized in table 2.

Of the three components of the formation the mudstone has the largest stratification index (398) and limestone the smallest (88). The beddedness of several units of the formation also may be compared by their stratification indices as follows:

Unit	Stratification Index	
Limestone no. 17	44	thicker-bedded
Limestone no. 13	77	thinner-bedded
Mudstone no. 18	144	thicker-bedded
Mudstone no. 9	467	thinner-bedded
Sandstone no. 11	100	thinner-bedded
Sandstone no. 3	55	thicker-bedded

The stratification index may be a useful method of expressing quantitatively the difference in beddedness of units, members, or formations. Beddedness or stratification indices may also be used for cross-bedding and such numerical or

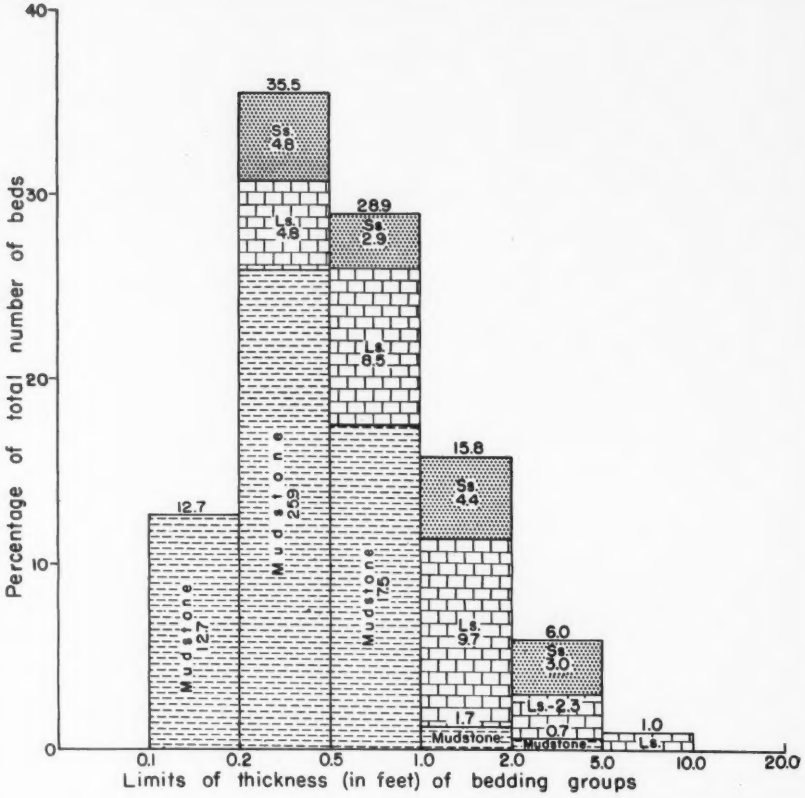

FIG. 3.—Bed thickness histogram of the Beta formation.

statistical data may prove useful in distinguishing genetic cross-bedding types. Furthermore, when sufficient indices have been determined it may prove possible to establish numerical limits for certain environmental or spatial conditions within genetic types.

The median bed thicknesses are determined from the cumulative curve. It may be noted with the hypothetical Beta formation (figs. 3, 4) that all the medians are less than the means which fact reflects the skewness or asymmetry of the frequency distribution.

The task of completely measuring a section bed by bed is great and commonly nearly impossible. Lack of good exposures is the most difficult obstacle. However, many units can be almost completely exposed by shallow trenching and for detailed studies of lithology this is often done. It may be useful to make the effort to measure individual beds, and where the practice is adopted much more accurate data concerning the lithology and kind of stratification as well as thickness are obtained. Also where complete exposures are not available it

TABLE 1.—*Bed count of Beta formation (m, mudstone; s, sandstone; and l, limestone)*

No.	Thickness Intervals (Feet)[1]							
	.05–.1	.1–.2	.2–.5	.5–1	1–2	2–5	5–10	10–20
18		10	9	6	5	2	1	
17				4	2		2	
16		25	16	7	1	1		
15					2	3		
14 m		4	25	5				
14 s			10	6	5			
13				2	7	4		
12 m			16	18				
12 l				6	2			
11					4	1		
10				5		2	2	
9		13	8	5	2			
8					2	2		
7		6	10	3				
6			21	15	26	3		
5 m			15	20				
5 l				5	3			
4 m			20	17				
4 s			13	7	4			
3					3	3		
2				1	4	2		
1						4		
Totals:		58	162	132	72	27	5	
		m-58	m-118 s- 23 l- 21	m-79 s-13 l-40	m- 8 s-20 l-44	m- 3 s-13 l-11	m-1 s-0 l-4	

[1] The intervals used here approximate the U. S. monetary units from a half dollar increasing to 20 dollars, a fortunate coincidence.

may be possible to "sample" the section where exposed for the beddedness characteristics. Lithologic and chemical sampling of rocks is rarely all inclusive.

The crux of detailed bed-thickness measurements is the bedding plane or surface. Although these are commonly very clearly defined features there are numerous rather vague changes in bedding, and probably all gradations between sharply marked bedding surfaces and obscure fabric changes occur in sedimentary rocks. Recent writers (McKee and Weir, 1953, p. 382) have at-

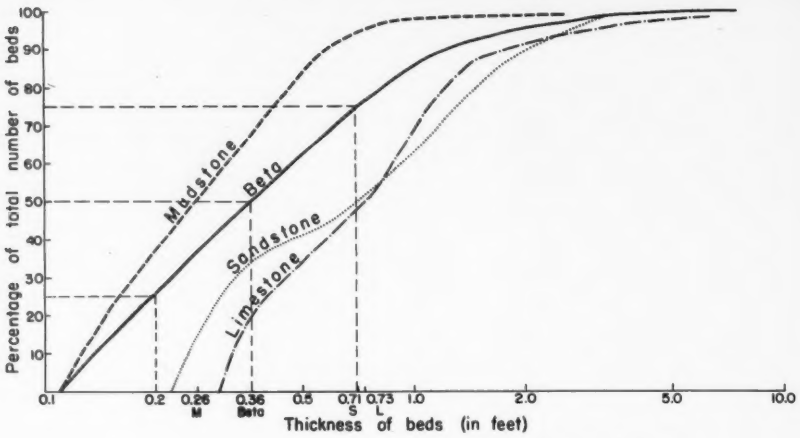

FIG. 4.—Cumulative curves of the Beta formation and its components.

tempted to distinguish between bedding surfaces and parting (splitting) on the basis of abruptness of the change, but abruptness of change is qualitative and the distinction between the two is subjective. Parting in shale or clay may be easily distinguished from bedding as a rule, but the distinction in sandstone or limestone-shale intercalations may be difficult. Thin-sections of shale may show laminae as thin as 0.05 mm (Rubey, 1930, p. 40) which if "counted" as beds would yield a stratification index of 6100. These laminae contribute to the fissility of the shale but would not ordinarily be "counted" as beds. If, however, such counting were done under the microscope statistical treatment might still be employed and such terms as *microbed index* or *varving index* might be used.

The subtle fabric changes parallel to the bedding, which are defined by some as parting, are commonly accentuated by weathering so as to make them appear as bedding surfaces. Furthermore, shearing parallel to the bedding during folding commonly develops a sort of pseudobedding surface so that moderately to steeply inclined beds in hogbacks usually appear more thinly bedded than the same beds in flat-lying outcrops. This raises the very fundamental question as to whether the terms "bedding plane, fissility, or parting" should be restricted to features of depositional origin or whether the term should include certain diagenetic and deformational breaks (shears) developed parallel to the bed. In any event it may be possible by comparing the bedding index of some unit in a gently dipping position with the index of a steeply dipping position and express numerically the degree of shearing parallel to the bedding.

Although the practice of counting bedding surfaces and measuring the thickness of each unit is subjective, it may be no more so than much lithologic sampling by units.

In regions, where for lack of outcrops, bed counting and measurements may not be done on the surface, cores or electrical logs may be used. Admittedly the electrical log records may not give all the beds yet they may give a degree or special aspect of thinness or thickness of

TABLE 2.—*Summary data of Beta formation*

	Beta Formation	Mudstone	Sandstone	Limestone
No. of beds	456	267	69	120
% of number		58.5	15.2	26.3
Thickness	265	67	61	137
% of thickness		25.3	23.0	51.7
Mean thick. (feet)	0.58	0.25	0.88	1.14
Modal thick. (feet)	0.2–0.5	0.2–0.5	1.0–2.0	1.0–2.0
Med. thick. (feet)	0.36	0.26	0.71	0.73
Thick. range (feet)	0.12–8.0	0.12–6.0	0.22–4.0	0.3–8.0
2^d quartile (feet)	0.2–0.7	0.16–0.42	0.3–1.3	0.4–1.1
Sorting[1]	0.59	0.51	0.66	0.53
Strat. index[2]	172	398	113	88

[1] Sorting $= \sqrt{Q3/Q1}$

[2] Stratification index $= \dfrac{\text{no. of beds} \times 100}{\text{thickness}}$

porosity units which may be useful as shown recently by Potter and Siever (1955, pp. 441–443).

The quantitative study of stratification may be useful in recognition of certain formations that are lithologically rather similar, as in the case of certain mudstone or black shale sequences. The careful determination of stratification indices for a single formation may enhance facies studies. Thus, there may be said to exist in a formation a stratification facies (phyllofacies?) as well as a biofacies or a lithofacies, and it may be just as productive of understanding of source and origin of a formation to determine regionally the stratification indices or ratios as it is to study sand-shale ratios. Two formations, each about 1000 feet thick, might have sand-shale ratios of 0.5, but one might have a stratigraphic index of 30 and the other 600. Certainly there would be a great deal of genetic significance in such differences of bedding that would not be expressed in the sand-shale ratio. It may be possible and useful to construct regional iso-stratification (isobed) maps just as it is to construct isolith maps.

In summary, some sort of partitioning of bed thicknesses is necessary for quantitative studies of beddedness, but care should be exercised in standardizing units for pigeon-holing of bed thicknesses and assignment of standard values for "laminae," "thin-bedded," and "thick-bedded." Statistical analysis of thickness frequencies and establishment of some sort of stratification index for regional studies of source, transportation, and deposition of sediment appear to be desirable in stratigraphy. I am convinced from my considerations of the quantitative or statistical approach to bed thickness that the additional effort yields a much better awareness and appreciation of the nature and significance of bedding than without such an approach. If these methods are adopted it appears that in time as numerical and frequency-curve data accumulate some unexpected and useful facts concerning stratification of sedimentary rocks may be revealed.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 4, PP. 301–306
FIG. 1—DECEMBER, 1956

SEDIMENT DISTRIBUTION IN THE SOUTHERN OCEANS AROUND ANTARCTICA

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ABSTRACT

The distribution of sediment types is shown on a map drawn on a polar projection, which covers the southern oceans northward to 52° S. Latitude on two margins and to 19° S. Latitude in the corners. The type of bottom sediment at over 500 stations, as reported in the literature prior to 1947, has been plotted. To this information have been added data obtained by the writer and others engaged in the U. S. Navy Antarctic Expedition of 1946–47. Sediment distribution boundaries are shown, based in part on those previously published on other projections, and adjusted to conform to the latest available information.

In general, Antarctica is bordered by a deposit of glacial marine sediment which roughly coincides with the area of pack ice; the next zone to the north contains diatom ooze which extends northward to the position of the Antarctic convergence or to the line where the Antarctic surface water turns under normal open ocean water. North of the convergence, in the open ocean, the bottom sediment is red clay in the deeper water and a calcareous ooze in the shallower water. Near shores, "terrigenous" sediments of various kinds are found. There are many local variations to this pattern.

The map is published in order to present the known data on a polar projection, and to indicate the need for further information from vast areas of ocean bottom in these regions which have never been sampled. Stratification of the sediments is discussed, and the need for study of core samples of the bottom is emphasized.

INTRODUCTION

The distribution of sediment types in the southern oceans has been illustrated in previous publications, but never on a polar projection. This projection gives a much better presentation.

The map (fig. 1) originally was prepared in 1947 with the expectation that it would be published in the reports of "Operation High Jump," the U. S. Navy Antarctic Expedition of 1946–47. Because funds for an elaborate report were not made available, the responsibility for publication of the map was returned to the author. Because of renewed interest in Antarctic exploration in connection with the International Geophysical Year programs, the map has been brought up to date and it is published here in order to record what is known and to serve as a guide to future s udies.

SOURCES OF INFORMATION

The geographical features of figure 1 are based on the U. S. Navy Hydrographic Office chart no. 2562, of 1943.

The reports of the various oceanographic expeditions which visited the southern oceans prior to 1947 provided most of the bottom sediment information represented on the map (fig. 1). The literature sources are listed under "References" at the end of this paper. A card was filled out with the data on the nature of the bottom at each station as reported in the literature. Most of the bottom samples reported were surface grab-bucket or dredge samples, but a few were short core samples. The type of sediment in only the uppermost part of each sample has been plotted on the map. The stratification found in some of the cores will be discussed in a following section of this paper. In addition to the published material, the writer has contributed information from nine core samples he obtained while on board the U. S. Coast Guard vessel, *Northwind*, attached to the central wing of "Operation High Jump," and Dr. Robert S. Dietz made available the information he obtained while with the western wing of

that expedition. More recently Dr. Willis L. Tressler has collected 24 bottom samples or cores from the *Atka* and 35 samples were taken in 1956 from the *Glacier* and the *Edisto*. The writer is indebted to Dr. Tressler and to Mrs. Suzanne F. Bershad of the U. S. Navy Hydrographic Office, Division of Oceanography, for providing the information on these samples and for additions to the list of references to publications.

SEDIMENT DISTRIBUTION BOUNDARIES

The world-wide distribution of pelagic sediments was first mapped by Sir John Murray and his associates from the data of the Challenger Expedition. Further investigations have changed the boundaries but have not materially affected the general picture.

The sediment boundaries as shown by a number of publications (including G. Schott, 1935; W. Schott, 1939, p. 398; Sverdrup, Johnson and Fleming, 1942, p. 975) were plotted on the work sheet for figure 1 in order to record the judgment of the various writers. The present writer then drew his own boundaries where there was diasgreement between the authorities or where new data gave further information. Certain basic relationships are observable where the sediment boundaries are controlled by adequate data. These are: (1) the glacial marine sediments generally coincide with the area enclosed by a line marking the average maximum extent of pack ice; (2) the northern boundary of diatom ooze tends to coincide with the Antarctic convergence; and (3) north of the Antarctic convergence and in the open oceans away from continental margins, red clay occurs in the deeper areas while the calcareous oozes occur in the shallower areas. These relationships have been used as a guide in drawing the boundaries in the areas where no information is available on the bottom materials.

The boundaries between sediment types, as shown in figure 1, must be understood to be approximations and subject to revision. The different sediment types grade into each other, and may be separated only on an arbitrary basis. There are vast areas of ocean bottom within the map area from which no samples have been taken and in which the topography of the bottom is not known in detail.

THE MAJOR TYPES OF SEDIMENTS

Figure 1 gives a letter symbol indicating sediment type at each station where a sample has been taken. The symbols are explained in the legend (fig. 1) and also are placed in parenthesis after the names of the types in the following discussion.

Glacial marine sediment (G) is composed mainly of material which has been transported from the land or shallow water by ice-rafting, and has been dropped to the bottom when the ice melted. It is composed of a wide range of particle sizes, from clay (less than 0.004 mm in diameter) to gravel (greater than 2 mm in diameter). The finer fractions consist more largely of silt rather than the clayey material that is typical of the common oceanic blue mud. The sediment may be unlaminated, and it has the general appearance of glacial till. The color generally is gray or grayish buff. Various organic remains may be present; these include diatom and foraminiferal tests. The calcium carbonate content is relatively low.

Glacial marine sediment is a special type of terrigenous sediment which was not given special recognition by the early investigators. Philippi (1912) first used the term "glacial marine deposits" for sediments collected by the *Gauss* near the ice front in Antarctic waters. The water in the zone of pack ice contains a large population of diatoms, as shown by plankton-net hauls. The sea ice in the Ross Sea frequently has a brown zone just below the snow cover, and in the Bay of Whales in February, 1947, the sea ice had a bright green zone just below the snow cover. Samples of ice

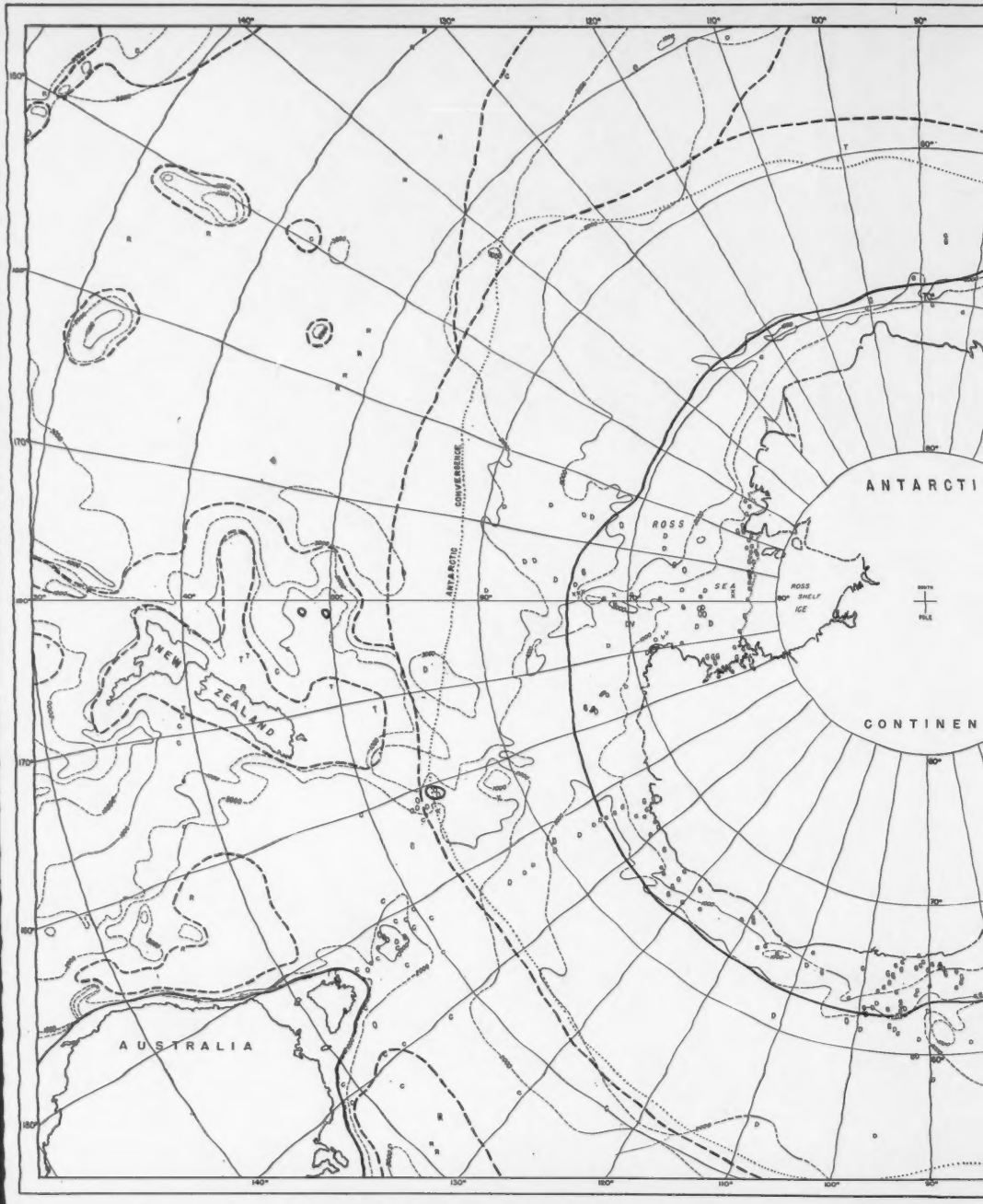
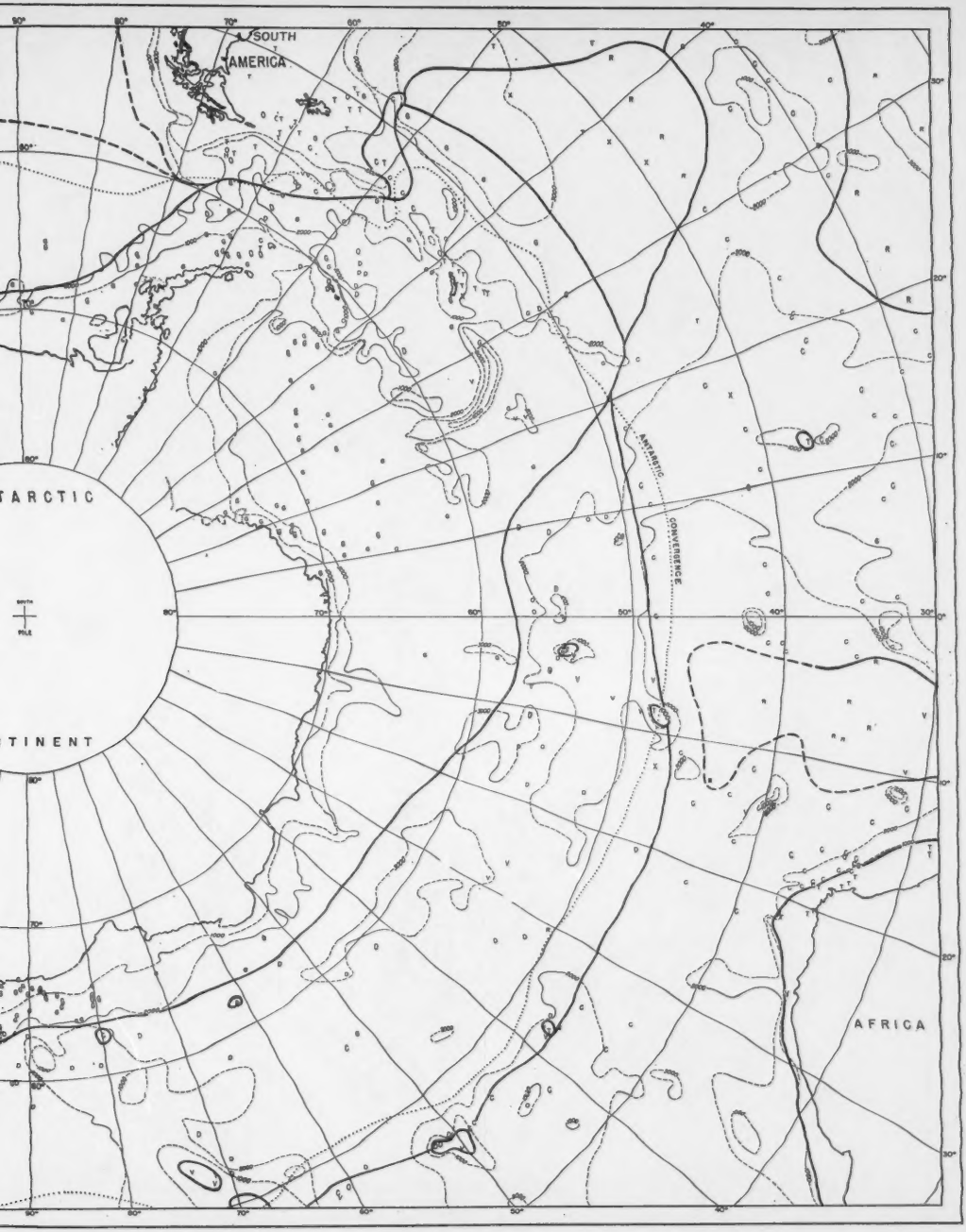


FIG. 1.—*Sediment distribution in the oceans around Antarctica. Key to letter symbols:* C, carbon
O, hard bottom, rock, or no sample; R, red clay; T, terrigenous sediment; V, v



: C, carbonate ooze (mainly globigerina ooze); D, diatom ooze; G, glacial marine sediment;
ment; V, volcanic materials; X, unclassified. Contour interval 1000 fathoms.

from these zones, collected by the writer, were melted and were found to contain a large quantity of diatoms. The glacial marine sediment in the pack ice area contains abundant diatoms; and because the northern limit of the pack ice fluctuates from year to year there must naturally be a gradation between glacial marine sediment and the typical "diatom ooze" in the next zone to the north.

The material at a few stations in and near the Ross Sea, within the glacial marine zone of figure 1, was reported by Schott as diatom ooze. Because the writer found diatomaceous glacial marine sediment in the same area, all of the material in question is here interpreted as glacial marine.

Diatom ooze (D) is composed mainly of the frustules of diatoms which have settled to the bottom from the uppermost layer of water. According to Sverdrup, Johnson and Fleming (1942, p. 984), the average composition of 21 representative samples of diatom ooze is as follows: Siliceous remains, mainly diatom frustules, 65 percent; calcium carbonate, mainly planktonic foraminifera, 8 percent; mineral particles, >0.5 mm in diameter, 10 percent; and mineral particles, <0.5 mm in diameter, 17 percent. The color of diatom ooze is yellowish, straw, or cream colored, and it is darker near land where it is diluted with glacial marine sediment.

Diatom ooze forms beneath the zone of the cold, comparatively less saline Antarctic surface water, beyond the limits of pack ice. North of the Antarctic convergence, where the cold water sinks below the surface (Sverdrup, Johnson, and Fleming, 1942, p. 606), the warmer subantarctic water is at the surface; this supports a large population of lime-secreting foraminifera. The Antarctic convergence is, therefore, generally the northern boundary of diatom ooze.

Calcareous oozes (C) are represented in the southern oceans mainly by globigerina ooze. By definition, a calcareous ooze contains at least 30 per cent calcium carbonate. The average composition of 772 samples of globigerina ooze has been given as follows: Calcium carbonate, mainly planktonic foraminifera, 64.7 percent; siliceous remains, 1.7 percent; mineral particles >0.5 mm, 5.1 percent; and mineral particles <0.5 mm, 28.5 percent (Sverdrup, Johnson and Fleming, 1942, p. 984). The color of globigerina ooze in the deep sea ranges from chalky white to yellow, brown, or rose with increasing percentage of mineral matter and iron oxides. Near land it may be dirty white, gray, or blue.

Depth of water has a marked effect on the distribution of globigerina ooze. A review of the bottom information at 66 stations in the southeastern Pacific ocean shows that only globigerina ooze occurs above a depth of 3600 meters, that only red clay occurs below 4100 meters, and that either globigerina ooze or red clay may occur between these two depths, depending on the locality (Hough, 1953, pp. 254–256). The approximate depth boundary between these two sediment types is somewhat different at the same lattitude in different ocean basins (Sverdrup, Johnson and Fleming, 1942, pp. 1004–1005).

Globigerina ooze is present at a few localities within the zone of Antarctic surface water, where it occurs as isolated patches in the diatom ooze zone. These generally are restricted to comparatively shallow areas.

Red clay (R) by definition contains less than 30 percent calcium carbonate. The average composition of 196 samples was as follows; calcium carbonate, mainly pelagic foraminifera, 9.0 percent; siliceous remains, 1.3 percent; mineral particles >0.5 mm, 3.5 percent; mineral particles <0.5 mm, 86.1 percent (Sverdrup, Johnson and Fleming, 1942, p. 984). In the South Pacific and Indian Oceans the color is chocolate brown; elsewhere it is a brighter red. The finest size fractions of red clay (as well as of globigerina ooze and blue mud) contain the common clay minerals. It is now generally believed that red clay consists largely of a finely-divided clay suspen-

sion derived from the land and transported by ocean currents and that the red color is caused by oxidation of the extremely slowly deposited material. Though it is probably of terrigenous origin, red clay is classified as a pelagic deposit.

Terrigenous sediment (T), as mapped in figure 1, includes blue, gray, and green muds, and all other terrigenous sediments which are not specifically excluded. As a group, it is found relatively close to shore, but there is a large area extending eastward from southern South America which is mapped in the terrigenous type. The terrigenous sediments are composed mainly of clastic mineral particles. The blue and gray colors probably are a result of comparatively rapid deposition and incomplete oxidation. The green color is caused by glauconite in some sediments but in others it may be caused by chlorite.

Glacial marine sediment is a special type of terrigenous sediment which has been mapped separately. In the region between the southern tip of South America and the Palmer Peninsula of Antarctica and to the eastward the glacial marine type is shown as extending northward to border the terrigenous sediment belt of South America. It is possible that some of the material in this region has not been correctly classified. In the vicinity of the islands of the South Georgia-South Sandwich group the shallow-water sediments are undoubtedly terrigenous, at least in part.

Volcanic materials (V) have been noted at a few places, most commonly in some of the *Valdivia* samples taken in the sector between 0° and 30° East Longitude and between 48° and 57° South Latitude. Some of the *Challenger* samples taken west of the Kermadec Islands in the area between 177°–179° E. and 28°–31° S. are described as volcanic mud.

Hard bottom (H) includes those stations reported as "hard bottom," or "rock," or "no sample."

Unclassified materials (X) include a very few materials whose descriptions did not clearly identify them with one of the foregoing types. A discussion of them is beyond the scope of the present paper.

STRATIFICATION OF THE SEDIMENTS

The foregoing discussion has dealt with the areal distribution of sediment types on the present surface of the ocean bottom. Several core samples have shown the presence of two or more types of sediment within a few feet of the surface. Philippi (1912, pp. 431–434), in his study of samples taken by the *Gauss*, found that glacial marine sediment occurred on the present surface of the bottom only about as far north as the northern limit of pack ice. Core samples from farther north, however, showed that glacial marine deposits extend northward beneath the diatom ooze. Cores from still farther north contained glacial marine deposits below a layer of globigerina ooze. These facts were interpreted by Philippi as a record of a northward extension of the pack ice during the Pleistocene epoch.

Schott (1939, pp. 405–407) has reviewed several other occurrences of stratification in core samples involving red clay, globigerina ooze, diatom ooze and glacial marine sediment. Up to the time of Schott's review all of the cores obtained were relatively short, and no method of dating the material had been developed. The available information showed, however, the widespread effect of relatively recent (presumably late Pleistocene) climatic changes on distribution of the sediment types. The northern boundaries of the glacial marine and diatom ooze types have moved farther south, and the area covered by globigerina ooze has increased by extension both to higher latitudes and to greater depths.

The writer (Hough, 1950) has described the lithology of three of his core samples from the Ross Sea which have been dated by a radioactivity method (Urry, 1949, and personal communication). These contained alternations of

glacial marine and non-glacial sediments, with fairly conclusive records of the altithermal (xerothermic, or "climatic optimum") time, multiple glaciation during the Wisconsin stage, the Sangamon interglacial stage, and the Illinoian glacial stage. By extrapolation of the time curve in the longest core, coarse-grained glacial marine strata were dated as Kansan and as Nebraskan. The longest core was 228 cm in length. It is predicted that a somewhat longer core, which could be obtained easily with modern equipment, would extend into pre-Wisconsin material.

A dated core sample containing several layers of red clay and globigerina ooze, taken in the southeastern Pacific, contains what has been interpreted as an even more detailed dated record of Pleistocene climates, from the Kansan glacial stage to the present (Hough, 1953).

CONCLUSIONS AND RECOMMENDATIONS

Further detailed mapping of the present areal extent of sediment types would be of some value in extending our knowledge. However, the refinement in accuracy of the sedimentary boundaries is not likely to produce any significant change in our concepts of the deep sea sediments. There is still much to be learned, on the other hand, from core samples which show stratification. Short cores taken along lines crossing the present boundaries of the glacial marine and diatom ooze zones and extending northward should reveal more details of the former extent of the pack ice and possibly of the northward displacement of the Antarctic convergence during late Pleistocene time. A few long cores, particularly if arrangments can be made for accurate dating of the material, may be expected to yield a wealth of information.

In core sampling north of the Antarctic convergence, it is recommended that samples be taken between the depths of 1800 and 2500 fathoms, because experience has shown that this depth range is most sensitive to climatic change.

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FIGS. 1–3, DECEMBER, 1956

EXAMPLES OF PROBABLE LITHIFIED BEACHROCK

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ABSTRACT

Probable lithified beachrock has been examined in sediments of Permian, Paleocene, Eocene and Miocene age. Brief, general descriptions of several of these exposures are given. The name, Lagunita, is applied to a Permian beachrock in New Mexico. Lithified beachrock may be mistaken for travertine, limestone conglomerate, intraformational conglomerate, and tectonic breccias. The presence of beachrock does not necessarily indicate the position of a continental shoreline.

INTRODUCTION

Kuenen (1950, p. 434), Emery (1953), Ginsburg (1953), Illing (1954), and Morgan and Treadwell (1954) have provided discussions of modern *beachrock* or *cayrock*.

Kuenen defined beachrock (called by him "beach sandstone") as a clearly stratified, generally dipping series of calcarenite beds, commonly found between tide levels. He specified layers 10 to 20 cm thick, of fairly uniform hardness, comparable to that of poorly cemented sandstone. His diagram (Kuenen, 1950, p. 435, fig. 178) shows a dip of 15°. He defined cayrock (called by him "cay sandstone") as forming in horizontal strata that may attain thicknesses of more than half a meter, with hardness varying from scarcely cemented to firm limestone.

Treadwell (1954) identified beachrock in the (Upper Eocene) Moodys Branch formation of Louisiana.

It is the purpose of this paper to list several additional possible beachrock beds in the geologic column, and to point out certain possible misinterpretations.

The work on the Lagunita formation and on the clastic limestone members of the Yeso formation was carried out in the summers of 1949 and 1954. The Tertiary exposures in Georgia, Florida, and Alabama were visited during the fall and winter of 1954–55.

LAGUNITA FORMATION

The San Andres formation (Permian) of the foothills of the Sangre de Cristo Mountains of New Mexico has been divided into three members (i.e., Northrop et al., 1946). The upper siltstone member was raised to formation rank and given the name, Bernal (cf. Kelley, 1949; Allen and Jones, 1952; Bachman, 1953). The lower sandstone was given formation rank with the name, Glorieta (Rich, 1921).

The middle, clastic limestone member is here named the Lagunita formation of the San Andres group. The name is taken from the village of Lagunita, near the Santa Fe railroad between Las Vegas, N. M., and Santa Fe, N. M. (approximately 35°23′, 105°14′). The village is quite inaccessible except by the most primitive kind of dirt road. A better and more accessible exposure is available at the northwest corner of the base of Chapelle hill, on the Santa Fe railroad, between the villages of Chappelle and Bernal (approximately sec. 36, T. 14 N., R. 15 E.). "Chapelle" was not selected as the formation name, however, because of the similarity to the (Mississippian) Chappel formation of central Texas.

The Lagunita formation is a contorted, brecciated, vuggy limestone, between a few inches and about 90 feet thick in the outcrop area. Generally the thickness does not exceed 20 feet. The

FIG. 1.—Yeso clastic limestone near the village of Tecolote, in the foothills of the Sangre de Cristo Mountains, New Mexico. The less accessible Lagunita limestone has the same general appearance.

formation is non-fossiliferous in the exposures located above, but grades down-dip (southeastward) into a marine fossiliferous limestone.

The gentle penecontemporaneous contortions, the brecciated character, and the many vugs and larger solution openings give the limestone an over-all appearance similar to that of travertine. The lack of megafossils is consistent with such an interpretation. However, detailed examination of many exposures and hand specimens leads this writer to the conclusion that the Lagunita is typical beachrock, altered slightly by later solution and recrystallization. The fetid odor given off when struck, the increase in thickness down-dip, the gradation to a fossiliferous marine limestone down-dip, and the nature of the angular fragments support the beachrock theory.

The Lagunita resembles, in many respects, the clastic limestones of the Yeso formation (see below). The angular fragments are, however, larger, more numerous, and more highly colored. Fragments in the Lagunita formation are pink, red, gray, dark blue, green, and yellow. They commonly occur in the pebble and cobble size ranges. Although a few foreign lithologies have been found, most of the fragments are limestone.

In the vicinity of Chapelle hill, the Lagunita may be seen in the sandy, dry bed of Bernal (Los Tres Hermanos) Creek, and in gullies north of the creek and west of the hill. Immediately overlying the Lagunita, and making up the lower half of Chapelle hill, are the distinctive orange siltstones and thin white beds of gypsum of the Bernal formation. To the north and west, forming a pronounced cuesta, are the yellow and white sands of the Glorieta formation, which lies below the Lagunita.

Another good exposure of the Lagunita may be found on the west flank of Esterito dome, on the Pecos River east of Dilia, N. M.

YESO FORMATION

The Yeso formation (Permian) in the foothills of the Sangre de Cristo Mountains of New Mexico is a thin-bedded, ripple-marked sandstone having a distinctive burned-orange color. The color

contrasts sharply with the purple shales and white arkoses of the underlying Sangre de Cristo formation, and with the yellow and white sandstone of the overlying Glorieta formation.

The Yeso generally contains, within the uppermost 75 feet, one to three beds of contorted, brecciated, vuggy dolomitic limestones separated by typical Yeso sandstones and siltstones. In a few localities, no limestones are present in the Yeso, either by non-deposition or because of subsequent erosion.

The Yeso clastic limestones are similar to the Lagunita formation, having the same general appearance of travertine. The position in the section, the thickening down-dip (to the southeast), and the nature of the clastic fragments contradicts the travertine interpretation. The Yeso clastic limestones, as examined in many places, are typical examples of beachrock, slightly altered by solution.

Good exposures of Yeso limestone may be seen in roadcuts along U. S. Highway 84–85, between the villages of Tecolote and Bernal (between Las Vegas, N. M., and Santa Fe, N. M.); and on the valley walls of Cañon Blanco, south of Glorieta Mesa and west of Villaneuva (fig. 1).

TAMPA FORMATION

The Tampa formation (Miocene) is a dull-white limestone alternating with calcareous shale in southwestern Georgia and the eastern part of the Florida panhandle. At places it has a pronounced clastic character. Excellent examples of the clastic facies may be found along the Atlantic Coast Line railroad one to two miles west of Recovery, in extreme southwestern Georgia (fig. 2). Cooke (1943) described the Tampa of the Recovery area as "... conglomeratic or brecciated, as if the partly consolidated rock had been broken by violent waves and redeposited." Cooke also described Tampa brecciated limestone exposures at Wylie Landing on Flint River, three miles above the mouth of Spring Creek and 3.5 miles north of the Florida line; at Brushy Cave, 200 yards north of the Thomasville road, 2.25 miles north of Climax and 8.5 miles east of Bainbridge, Ga.; and at Forest Falls, 6.5 miles north of Whigham (Grady County, Ga.).

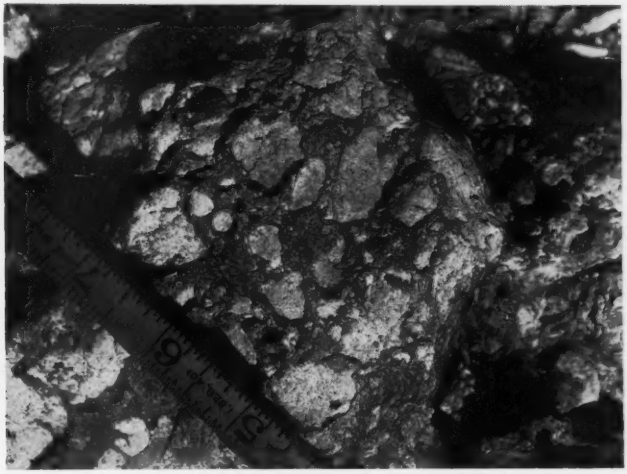

FIG. 2.—Close-up of the Tampa clastic limestone exposed near Recovery, Ga. Many of the individual fragments have been blunted or rounded.

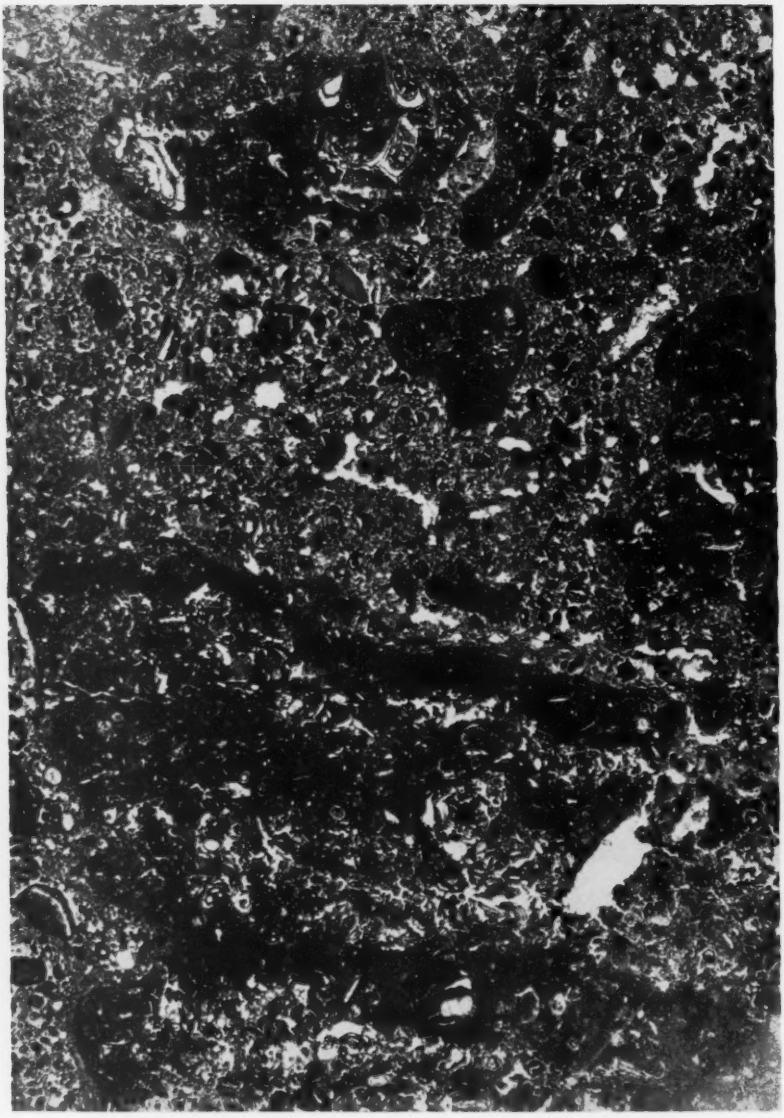

FIG. 3.—Microscope slide cut from the Tampa clastic limestone. The sample was collected near Chattahoochee, Fla., by William Yon and Charles Hendry of the Florida Geological Survey. Magnification, about 10× (linear).

Clastic Tampa also occurs in exposures along the walls of the valley of the Apalachicola (i.e., Chattahoochee) River, in the vicinity of the town of Chattahoochee. The slide (fig. 3) was made from a sample collected in this locality by William Yon and Charles Hendry of the Florida Geological Survey.

The silty, clastic facies of the Tampa has been referred to as the Chattahoochee (Puri, 1953; others). To the southeast this lithologic type grades into the calcareous St. Marks facies, which contains a small proportion of quartz grains but no known beachrock.

Creamy white beachrock crops out in the bed of and along the banks of the Ochlockonee River, north and west of Tallahassee. One exposure may be seen south of the Lake Talquin dam, and north of the Florida Highway 20 bridge (the Jackson Bluff locality). This bed has been called Hawthorn (Cooke, 1945), but is probably Tampa, which it resembles, or Choctawhatchee.

TERTIARY OF GEORGIA

The Clayton limestone (Paleocene) exposed in the river bank under the highway bridge at Ft. Gaines, Ga., is locally a beachrock, although poorly indurated. The Crystal River limestone (Eocene) found along the bank of the Flint River, under the west end of the highway bridge at Bainbridge, Ga., is, in part, beachrock. In the latter instance, solution work by the river makes the clastic nature of the limestone difficult to recognize.

CONCLUSIONS

In order to reconstruct depositional environments of the past, the physical stratigrapher must integrate many kinds of information. In rare instances a single observed fact may establish a proposition. Many physical characteristics of sediments are susceptible to two or more interpretations. It is therefore necessary to amass as much factual material as possible before extensive inferences are made.

Beachrock observations—in the light of the above—must be handled cautiously.

1. It is quite understandable that certain beachrock exposures might be identified as travertine. The Lagunita and Yeso limestones, for example, are in many respects similar to the Brush Hollow travertine of the Cañon City reentrant of Colorado (Tanner, in press). The Brush Hollow, however, is a continental fresh-water deposit, containing evidences of land plants and snails.

2. Because the clastic fragments, formed in the early stages of beachrock accumulation, are soft and may be rolled for short distances, the final product may look much more like a limestone conglomerate than like a breccia. The Tampa limestone near Recovery, Ga., contains pebbles and cobbles which are rounded rather than angular (fig. 2).

3. Intraformational conglomerates derived from calcareous muds or oozes may have the general appearance of beachrock. In fact, beachrocks probably belong in the broader category of intraformational conglomerates, but this relation must not be read in both directions.

4. Tectonic breccias, produced in limestones and dolomites, in some instances may resemble beachrock.

The presence of beachrock, by itself, is not sufficient evidence for placing a shoreline in the vicinity of the exposure. The beachrock forming on the Dry Tortugas (Florida) today (Ginsburg, 1953) is located about 80 miles west of Key West, and about 150 miles southwest of the nearest mainland beaches. The modern cayrock in the Bahamas (Illing, 1954) is located 100 to 200 miles from Cuba or the mainland.

With other information, however, beachrock can be quite useful in describing and delineating environments of deposition.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 4, PP. 313–321
FIGS. 1–6, DECEMBER, 1956

THE CURLEY LIMESTONE—AN UNUSUAL BIOSTROME IN CENTRAL UTAH

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ABSTRACT

A laminated, fine-grained, pure limestone bed two to three feet thick with wave to dome-like structures superimposed on the laminae crops out in an area of 600 square miles in central Utah. The bed occurs near the middle of the Mississippian Gardner dolomite. Individual laminae of the bed range from .06 to 5 mm and average about .25 mm in thickness, while length may be several feet. Texture of the limestone is extremely fine-grained and only locally are microscopic structures, other than minute calcite crystals and light- and dark-gray laminae, visible. Dome-like structures superimposed on the laminae range to 10 cm in diameter and may be composed entirely of domed laminae or a hemispherical mass of rod to leaf-like crenulated gray bodies resting on horizontal laminae and covered by laminae. Epigenetic dolomitization has affected local areas of the bed, but distinctive structures are retained. Though both subaqueous slumping and organic origins have been suggested for the bed, the latter origin is strongly supported by megascopic and microscopic features related to organisms.

INTRODUCTION

A distinctive gray laminated limestone with wave to dome-like structures superimposed upon the laminae crops out in an area of at least 600 square miles west of Provo, Utah (fig. 1). The bed is 2 to 3 feet thick, fine-grained, and relatively pure. The broad areal distribution, relative constancy of thickness, unusual lithologic character, and stratigraphic position in the Mississippian system makes the bed unique among the numerous limestones and dolomites of the rather complete Paleozoic section exposed in this part of the state.

Crane (1912) first recognized the limestone bed in the Tintic Mining district. Later, Lovering (1949, p. 6) used the term "Curley bed" to denote this thin member of the Mississippian Gardner dolomite. Proctor (1951), Hoffman (1951), Williams (1951), and Rigby (1952) also describe the bed. Graduate students mapped it in Long Ridge, West Mountain, and the Boulter Mountain areas of central Utah. With all these notes no detailed study of the Curley bed appears to have been undertaken.

The uniqueness of the bed in regards to its relative constancy of thickness and distinctive lithologic structures over wide areas makes it seem worthwhile to present accumulated and new data on the Curley limestone. Areas of outcrop, structure, lithology, stratigraphic position, paleontology, microscopic features, chemical composition, and possible modes of origin are discussed.

STRATIGRAPHY

The Curley limestone occurs near the middle of the Gardner dolomite, a formation originally described by Loughlin (Lindgren and Loughlin, 1919, p. 39) as Lower Mississippian in age. Crane (1912) placed the bed 350 feet below the overlying Pine Canyon formation. More recent work on the Gardner formation by members of the U. S. Geological Survey (Proctor, 1954) confirms the stratigraphic position of the bed.

The Curley limestone lies conformably on pinkish-gray sub-lithographic stone (fig. 2) and grades almost imperceptibly from the dense and massive limestone below to a gray laminated slightly waved limestone and finally into the typical trough and dome-like structures of the laminae (figs. 3, 4).

Gray to dark-gray somewhat crystalline fossiliferous limestones lie directly

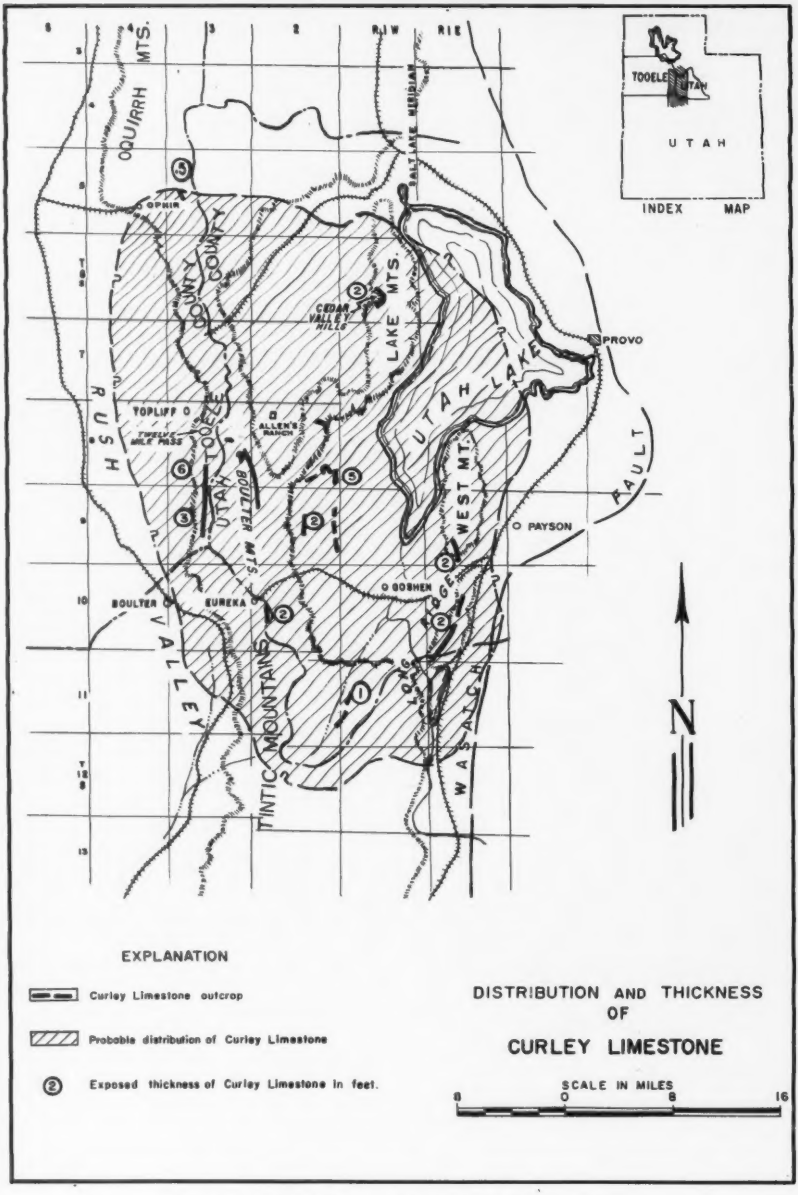

FIG. 1.—Distribution and thickness of Curley limestone.

above the Curley limestone (fig. 5). The beds range in thickness from a few inches to several feet. These commonly demonstrate a clastic texture with conspicuous local cross-bedding.

Outcrops of the Curley limestone are known from the west portion of the Boulter Mountains on the west to the Oquirrh Mountains on the north. Easternmost outcrops lie in the Lake Mountains and in the southern portion of West Mountain. The southernmost outcrops occur 7 miles south of Goshen, Utah, on Long Ridge (fig. 1).

The Curley limestone crops out just south of Eureka in the main Tintic mining district where it forms the boundary between the Mississippian upper and lower Gardner dolomite. Its thickness here averages 2 feet. A few miles to the north, Sargent (1952), Renzetti (1952), and Axenfeld (1952) noted a thickness of 3 to 6 feet for the bed where it crops out along the west side of the Boulter Mountains. A short distance northward the Mississippian section disappears under younger sediments in the Twelve Mile Pass area. Sediments of Mississippian age again appear at the surface in the Ophir area 18 miles north. Here Gilluly (1932) describes the Mississippian Madison limestone as lying on the Devonian Jefferson(?) dolomite. However, the very similar lithologic characteristics and faunal relationships of these two formations and the upper and lower members of the Gardner dolomite to the south suggest (Duncan, H., Gordon, M., Proctor, P. D., personal communication, 1952) that these formations are time equivalents, i.e., the so-called Jefferson(?) dolomite is the equivalent of the lower Gardner dolomite and the Madison formation the equivalent of the upper Gardner dolomite. A limestone bed 2 to 4 inches thick with slightly undulating laminae lies at the contact between the questionable Jefferson(?) and the Mississippian Madison formations. This thin bed resembles and probably represents the northernmost limit of the Curley limestone.

A Mississippian section similar to that described by Gilluly (1932) crops out several miles to the east in the vicinity of American Fork Canyon in the Wasatch Mountains. Field checks of the contact between the Madison and the doubtful Jefferson(?) formations failed to reveal the Curley limestone. Crittenden (per-

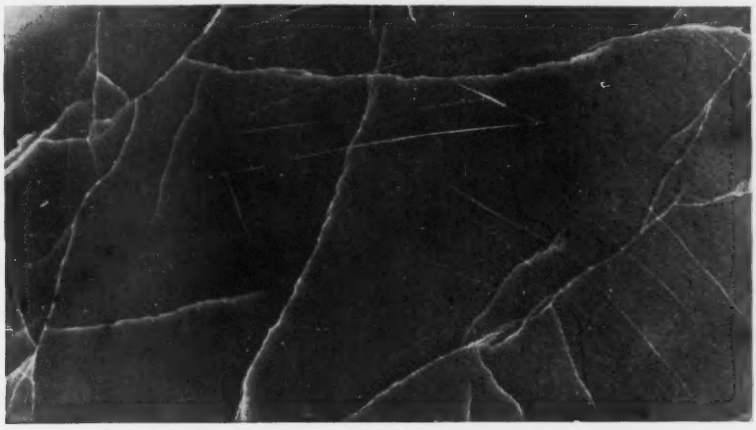

FIG. 2.—Sub-lithographic limestone below Curley limestone, Allen's Ranch quadrangle. Irregular light lines are calcite veinlets; straight lines are polish scratches (×7).

sonal communication, 1953) and Baker (1947) do not record its presence in the central Wasatch Mountain area.

Brown (1952) does not describe the Curley bed in the Wasatch Mountains just east and south of Payson. Both Calderwood (1951) and Bullock (1951) mapped the Mississippian Gardner formation in the Lake Mountains but do not mention the bed. However, it does crop out in the Cedar Valley Hills on the west side of the Lake Mountains. Here it dips gently eastward and is 2 to 3 feet thick.

Excellent exposures of the Curley limestone occur in the Allen's Ranch area where Johns (1950), Proctor (1951), Hoffman (1951), and Rigby (1952) record its presence. The thickness of the bed ranges from 2 to 5 feet, but averages a little more than 2 feet. Good outcrops of the bed also occur on the south end of West Mountain and farther south and west along Long Ridge. Here the bed dips generally eastward at moderate angles (Sirrine, 1953; Peterson, 1953; and Clark, 1953). Muessig (1950, p. 203) notes the Curley limestone in his measured stratigraphic section approxmately 7 miles south of Goshen, Utah. Here it is dolomitic in composition and only one foot thick.

In summary, boundaries of the Curley bed probably lie to the west of the Boulter Mountains in the Rush Valley area, north near Ophir, Utah, just east of the Lake Mountains, and south of Goshen, Utah. Actual outcrops are known in an area of over 600 square miles though the actual areal extent may be much greater.

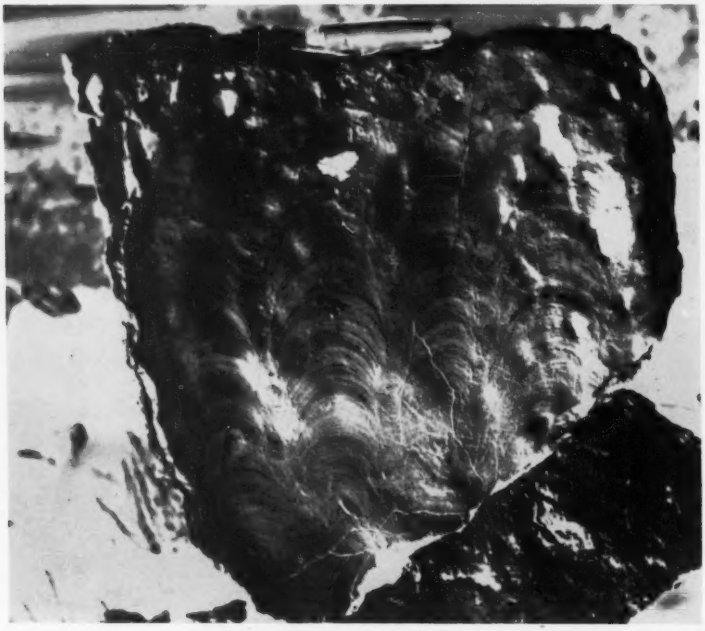

FIG. 3.—The Curley limestone bed, showing symmetrically domed laminae and narrow trough areas ($\times\frac{1}{3}$).

FIG. 4.—Domed laminae with adjacent broad trough area. Note that some vertical laminae cut out against other laminae. The trough area is composed of horizontal laminae with breccia-like limestone near the bottom and continuous laminae toward the top.

PALEONTOLOGY

Identification of the foraminifer *Granuliferella* in the limestone beds below the Curley bed dates these as Kinderhookian. The beds above contain *Plectogyra tumula* and probably are of upper Kinderhookian-lower Osagian age (Clark, 1954). Megafossils support these ages.

PETROGRAPHY

The laminae of the Curley limestone range from .06 mm to 5 mm in thickness and average a little less than .25 mm. They range from light gray to medium and sometimes dark gray (fig. 6). The light and dark laminae often alternate and form distinctive outcrops. Within the Allen's Ranch quadrangle and southeastward along Long Ridge, local dolomitization of the bed causes the color to change to shades of brown-gray and blue-gray.

Individual laminae are fairly persistent and can be traced several feet along the strike. Yet, on some of the domes, the laminae cover only the upper portion and appear to cut out against other vertical laminae on the lateral portions of the structure (fig. 4). The domes range in diameter from 4 cm to more than 10 cm. In places these structures lie close together with narrow but sharp synclinal-like troughs between them (fig. 3). Elsewhere the syncline-like structures are just as wide as the domes and as persistent. As already noted, the domes may project into the overlying strata, but generally both the troughs and domes disappear by gradual transition of the structures into relatively flat-lying laminae. These are in turn covered by medium-grained clastic limestone as described above.

The texture of the Curley limestone is extremely fine-grained. In several thin sections, calcite crystals composing the bed average less than 0.025 mm in diameter. Only 2 thin sections demonstrate any recognizable structure other than the megascopically visible laminae.

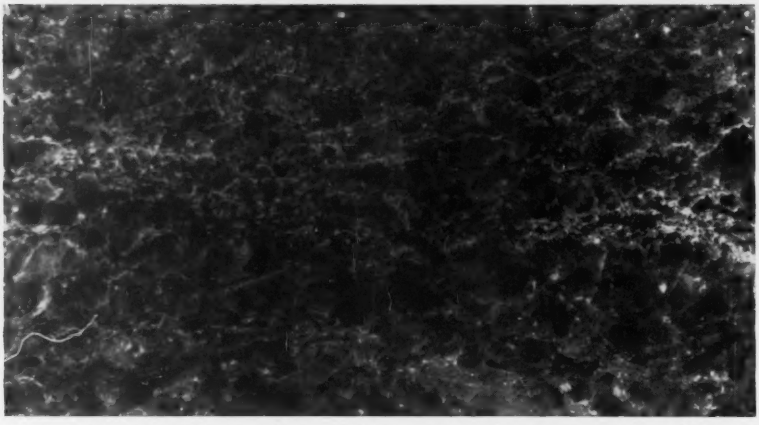

FIG. 5.—Clastic-textured, somewhat crystalline upper Gardner formation directly above the Curley limestone, Allen's Ranch quadrangle (×7).

In one locality minute gray calcite crystals form distinctive laminae in the bed. These thin and thicken along the strike. A lighter gray calcite mass with tooth-like projections of darker gray calcite fillings between develops toward the top of the individual laminae. These are overlain by similar laminae. Dome-like structures composed of rod to leaf-like crenulated light gray calcite masses locally rise to 3 cm or more above the essentially horizontal laminae. In general, the laminae appear to be essentially conformable above the dome, but the first two or three laminae lack the typical tooth-like projections and are somewhat more dense in appearance. The uppermost laminae gradually flatten and are covered by the upper Gardner clastic limestones. As noted, some of the domes locally project up into the upper Gardner limestone beds, though the distinctive internal structures described are not visible.

Though conclusive evidence is lacking, possibly many of the original structures between and associated with the laminae were probably destroyed either during diagenesis or at a later time.

Several samples were cut across the Curley limestone bed for purposes of chemical analyses. Results of two such channel samples are included in table 1.

TABLE 1.—*Chemical analyses of Curley Limestone bed Section* 1, T. 9 S., R. 3 W. *Utah County, Utah*

	1	2
CaO	55.10	54.70
MgO	.44	.50
SiO_2	.80	.68
Al_2O_3	.01	.01
Fe	.04	.08
P	.04	.01
S	.02	.02
Pb	.01	.01
Cu	.01	.01
CO_2	43.29	42.08

As already stated, local areas of the Curley bed have been altered to dolomite. The altered portions of the bed retain all of the megascopic characteristics of the unaltered portions except for a lighter color and somewhat more coarse-grained texture. For comparative purposes a partial chemical analysis of the unaltered, slightly altered, and intensely altered portions of the bed are included in table 2. Locally minute "saddle

reef" type fillings of dolomite and minor amounts of included calcite lie in the domal areas. These may represent original domes of the Curley bed as above described, but are now so intensely altered as to have lost their original identity.

TABLE 2.—*Unaltered and altered Curley Limestone bed*

	1. Unaltered	2. Slightly Altered	3. Intensely Altered
CaO	55.10	50.79	29.90
MgO	.44	4.05	21.61
SiO_2	.80	.55	.86
Al_2O_3	.01	.06	.15
P	.04	.10	.01
S	.02	.05	.03
Pb	.01	.01	.03
Ti	.01		
CO_2	43.29	44.36	47.29

1. Chip sample, Sec. 1, T. 9 S., R. 3 W.
2. Chip sample, Center Sec. 15, T. 9 S., R. 2 W.
3. Chip sample, Center Sec. 15, T. 9 S., R. 2 W.

ORIGIN OF THE CURLEY LIMESTONE

Numerous modes of origin have been suggested for the Curley limestone. These can all be included under two major theories: (1) Subaqueous slump origin, (2) An organic origin.

Rigby (1949) and Hoffman (1951) suggest the subaqueous slump origin. They state that the domes and basin-like structures superimposed on the laminae are probably the

"result of contemporaneous deformation due to subaqueous slumping on a gentle to moderate slope . . . and . . . slight instability of the shelf upon which the beds accumulated could have initiated the slumping."

Elison (1952), Peterson (1953), Sirrine (1953), Clark (1954), and later Rigby in a revision (1952) of his former work support an organic origin for the bed. None of the workers gives detailed reasons for the suggested origin. No associated microscopic structures are described, but note is made of the megascopic crenulations and dome-like forms.

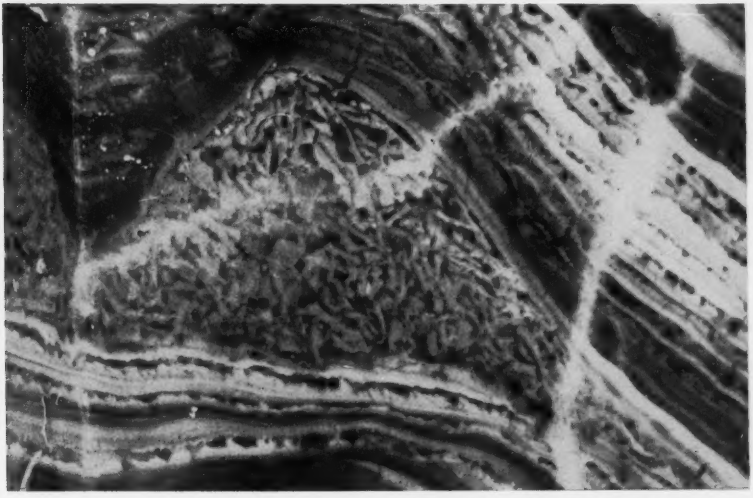

FIG. 6.—Portion of Curley limestone laminae and domal area showing internal structure, Allen's Ranch quadrangle. Cross-cutting lines are calcite veinlets (×7).

Certain field facts do not support an origin by subaqueous slumping of the beds. Among these are: the broad areal distribution of the limestone, its relatively uniform thickness throughout its known extent, continuity of individual laminae, and the tendency of the bed to gradually thin out at the known marginal areas. The lack of alignment of the fold-like structures within the bed, the dome-like character of these structures, local upward projection of the domes into the overlying bedded structures, dearth of rumple and fault structures, and almost complete absence of breccia and various other structures which would result from subaqueous gliding of the bed (Hill, 1953) also seem to rule out a subaqueous slump origin.

Clark (1953), Peterson (1953), and Sirrine (1953) each suggest a similarity of the bed to the alga genus *Codonophycus* from the Madison formation of Wyoming. No comparison of microscopic structures between the Curley limestone and *Codonophycus* appears to have been made though there is a striking megascopic similarity. Fenton and Fenton (1939) describe this biostrome-forming genus from the Mississippian Madison formation, time equivalent of at least a part of the Gardner dolomite.

More conclusive evidence supports the organic origin. A portion of the bed in the N½ Section 35, T. 8 S., R. 2 W. of the Allen's Ranch quadrangle shows microscopic branching threads in some of the laminae and leaf-like forms in the domal areas. Because of their resemblance to known organic structures, these were submitted to J. Harlan Johnson for study. His description (personal communication, 1955) is as follows:

"The specimen consists of laminations representing growth layers of 'algae felt.' As commonly happens, these are irregular and show alternations of thick, thin, and light and dark. The 'algae felt' represent calcareous molds of layers of felt-like masses of algal threads. The plants consisted of patches, layers or 'scums' of probably rapidly growing thread-like algae. The growing tips or surfaces were sticky and half sediment. Lime was deposited around the older parts of the mass. . . . The algae responsible represents structurally low forms belonging either to the green or blue-green algae."

His identification of alga structures confirms the field observations and suggested organic origin. The almost complete absence of recognizable microstructures may possibly be explained by his published comments (Johnson, 1951, p. 199):

"After the death of the plants a very porous calcareous mass is left which is easily attacked by circulating water and recrystallized. The cellular internal structure is usually destroyed in the process"

and from specimens submitted at a later date:

"The material is definitely algal. The limestone is formed of thin layers of laminae and pellets of calcareous molds of an algal felt. It is an unnamed type and there are few diagnostic features. . . . It belongs in Pia's general family of the Spongio-stromata. . . . Such algae have been found in rocks of all ages, from the Proterozoic to the present. . . . The thin layers or laminae in the limestone represent seasonal growth."

In summary, the broad distribution, rather constant thickness of the bed, the distinctive dome and trough-like structure, chemical purity, unique megascopic laminae, and critical microscopic structures typical of algal origin all lend strong support to the organic origin of this unusual limestone bed in central Utah.

ACKNOWLEDGMENTS

The writers are especially grateful for the critical suggestions and for the kind help of Professors W. L. Stokes and D. J. Jones of the University of Utah. Portions of the report are from an unpublished U. S. Geological Survey manuscript on the Allen's Ranch quadrangle, Utah, by the senior author.

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FIGS. 1–6, DECEMBER, 1956

MULTIVARIATE ANALYSIS OF MINERALOGIC, LITHOLOGIC, AND CHEMICAL COMPOSITION OF ROCK BODIES[1]

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ABSTRACT

The simultaneous evaluation of a number of mineral or chemical constituents in rock samples requires statistical methods designed to handle several variables at a time. This is accomplished for certain kinds of areal studies by use of a method especially designed to handle any number of variables that can be expressed as proportions or percentages, where the total adds up to 100 percent.

The statistical questions related to the design are concerned with the regional or local homogeneity of rock bodies at several sampling levels. Examples are included of pebble distribution in glacial drift, heavy minerals in beach sand, and the distribution of lithologic types in a subsurface stratigraphic unit. It is shown that in some instances there may be a broad regional homogeneity with smaller scaled heterogeneity superimposed upon it. The reverse situation may also occur. Extensions of the method permit comparison of two or more rock bodies in terms of selected constituents.

In addition to its uses in sedimentary, igneous, and metamorphic petrology, the method appears to have applications in paleontology, geomorphology, and other branches of geology. The statistical model, which crosses constituents with a nested sampling design, is described in a technical Appendix that also shows the method of computation.

INTRODUCTION

Heavy mineral analysis of sediments, pebble counts in glacial till, lithologic composition of stratigraphic units, modal analysis of igneous and metamorphic rocks, and chemical analysis of rocks in general yield percentage data on a number of constituents that make up the samples. Geological interpretation of the data requires simultaneous evaluation of all or several of the constituents to decide whether significant differences occur among the samples. Such evaluation is largely subjective and involves making allowances for the natural variation that may occur among groups of similar samples.

Most statistical methods used in geology have been univariate in that they treat one constituent at a time, with the result that individual comparisons may include some seeming contradictions. A set of heavy mineral samples may have varying amounts of garnet, zircon, tourmaline, and other minerals. The garnet proportions may suggest that the samples are similar whereas the zircon data may suggest that they are significantly different. When a number of such univariate analyses are balanced against each other, a composite judgment must be made on subject matter grounds. Such composite judgments, whether based on univariate statistical analysis or not, are difficult to express in quantitative probability terms.

Multivariate methods of statistical analysis are available for simultaneous treatment of several variables, but are calculationally complex and sometimes difficult to interpret. Burma (1950) described applications in paleontology, and Miller (1954) used a multivariate model to distinguish among the textural characteristics of beach and near-shore sands. The method introduced here is, we believe, useful in problems of variation in composition—for example, areal variation in rock composition, including facies changes in subsurface studies. The

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statistical questions that commonly arise in such areal studies include the following: is the rock mass or stratigraphic unit regionally homogeneous in composition? May there be one or more levels of small scale heterogeneity superimposed on the regional homogeneity? In some studies one encounters rock masses that seem to vary in composition locally, and yet they display a regional homogeneity on a larger scale. The reverse situation may also occur, in which closely spaced samples are very similar, whereas widely spaced samples are markedly different. When two or more rock masses or stratigraphic units are compared, they sometimes have similar average compositions but differ in the extent of their variability from point to point. In part, correlation of stratigraphic units by rock properties depends on variability at several levels, and in some studies it may be advantageous to express the relations numerically. Similarly the composition of igneous masses may be compared in terms of small or large scale areal factors.

Analysis of such problems requires a sampling plan that permits estimates to be made of the variability present at several sampling levels. The development of the sampling plan is a statistical problem, but the selection of the specific design is influenced by the kinds of data used and by subject matter questions that are raised. The present design combines parts of two standard statistical techniques in common use for univariate analysis. Methods of computation are standard, and the tests are formally similar to those used in conventional designs. In form the method includes a nested sampling plan combined with a cross-classification of constituents (types of minerals, etc.) expressed as transforms of percentages.

There is comparatively little geological data ready at hand to illustrate the method, although some published material can be rearranged slightly to demonstrate the kinds of analysis that are possible. Examples based on variations in pebble counts for glacial drift, heavy minerals in beach sand, and areal variation in a subsurface stratigraphic unit are presented as illustrations. The statistical inferences carry no necessary implications regarding the original geological study, inasmuch as only parts of the data are used to illustrate the method of setting up such examples.

OUTLINE OF THE STATISTICAL METHOD

Collection of samples in a nested design (sampling hierarchy) provides samples at several spacings so that the variability introduced at each sampling level may be estimated. This provides data for comparing the large and small scale effects in composition at as many sample spacings as there are levels in the hierarchy. When each sample is analyzed for the percentage of each constituent present (or for those considered to be particularly important in the study), data are available for simultaneous treatment of more than one attribute.

The essential device which allows us to approximately treat a multivariate problem by univariate methods is to focus our attention on the interactions between constituents and the variables to be studied, here the various sampling levels. In the present situation, the formal main effects of the variables to be studied turn out to be entirely irrelevant.

The statistical model, described more fully in the Appendix, involves crossing the constituents (types) with proportions (counts) in local areas within larger areal segments. In such a model a single observation, X_{ijkm} is represented as a grand mean plus contributions from the ith major sampling segment, the jth local aera in the segment, the kth count in the local area, and the mth type in the count, as well as from interactions between segments and types, localities and types, and counts and types.

The computations are set up in such manner that the total sum of squares can be partitioned into seven portions,

one of which is attributable to constituents, one to each sampling level, and one to each interaction. (Only the interactions are of interest.)

The original percentage data are first transformed by the arc sine square root transformation (e.g. Snedecor, 1946, p. 449), then in order to partition the total sum of squares into the required portions, the transformed values are summed over the various subscripts in the manner indicated in the Appendix. The degrees of freedom are distributed in a conventional manner over the several sampling levels, the types, and the interactions. The interaction mean squares are computed and approximate significance tests appropriate to certain questions are set up by taking ratios of these mean squares to obtain observed F values.

The use of, and choice among transformations may seem to require comment. When the constituents are not counted, as in lithofacies work, theory does not provide clear guidance, but when counted data are being analyzed, and the variation is either (i) purely binomial, or (ii) binomial combined with non-binomial variation which has relatively constant variance on the transformed scale, *and* the variables are of approximately equal subject-matter importance, theory indicates that the use of the angular transformation is appropriate. In all cases, experience with the analysis of proportions in other fields suggests that the angular transformation will be effective in geological problems.

EXAMPLES OF THE STATISTICAL METHOD

Pebble Counts in Glacial Drift

When pebble counts are made on samples from a single drift sheet it is sometimes observed that local variations are prominent, but that an underlying regional similarity may be discerned in the pebble composition. In some instances it is possible to differentiate drift sheets despite the local variability, especially when gross aspect, depth of leaching, dominance of particular lithologies, or marked differences in particle size distribution are present. In these well defined instances no formal statistical treatment is needed.

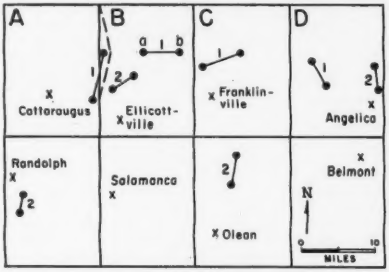


FIG. 1.—Map showing locations of Binghamton drift pebble samples, adapted from MacClintock and Apfel (1944). Quadrangle names are indicated by the towns marked with an x.

Statistical analysis can play an important part in studies where the variability within a local area of the drift sheet is of the same order of magnitude as the regional effects that are to be detected. In such instances it is desirable to collect samples according to a plan which permits evaluation of the variability introduced by different sample spacings. If in addition the tests for similarities or differences can be based simultaneously on a number of rock types present in the pebbles, the convergence of this multiple evidence may point toward a specific answer. This double requirement of variable sample spacing and multiple observations in the study of drift sheets is well met by the present statistical model.

MacClintock and Apfel's study of the Binghamton drift in the Salamanca reentrant, New York (1944), provides an excellent example for testing the local and large scale homogeneity or heterogeneity of a single drift sheet. MacClintock and Apfel collected till and outwash pebbles over an area of about eight quadranges. By some rearrangment of the original sampling plan it is possible to select a nested design for illustration.

In discussions with Dr. MacClintock, plus references to his original notes, it was possible to set up the design sketched in figure 1.

Each north-south set of two quadrangles was considered as a major sampling segment. In each segment (with one minor exception) it was possible to find two localities where pairs of samples had been collected reasonably close together. The distance between quadrangles, center to center, is about 13 miles, and the average spacing of localities within each segment is about 12 miles. The samples in each pair averaged about 4 miles apart. Ideally it is preferable to have the sample spacing decrease more regularly in nested designs, so that no two levels are as close together in sample spacing as the upper two in this illustrative example.

As rearranged, the sampling hierarchy provides for four major segments, two localities within each segment, and two counts at each locality. MacClintock and Apfel grouped the pebbles into six lithologic types plus a general class of locally derived pebbles. The local pebbles were omitted from the study, and the six rock types were regrouped into five by combining the igneous and gneissic types. The five groups are all considered to be foreign to the sampling area: limestone, red sandstone, chert, quartzite, and gneiss plus igneous.

Omission of the local pebbles illustrates a common decision that may be made in evaluating compositional attributes of rocks. In igneous rock studies, for example, abundant minerals may be omitted, with major emphasis on less abundant constituents. In heavy mineral studies likewise, the "flood" minerals may be omitted from some studies, and in chemical analysis of certain rocks major emphasis may be placed on trace elements (when a logarithmic transformation might be considered in place of the angular transformation). Omission of some types are subject matter decisions that do not affect the statistical design.

TABLE 1.—*Binghamton drift pebble percentages*
(Data from MacClintock and Apfel, 1944)

Segment	A				B				C				D			
Locality	1		2		1		2		1		2		1		2	
Count	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Limestone	54.1	57.1	46.9	40.0	59.4	43.6	59.4	69.0	71.8	70.3	58.1	69.8	44.4	61.2	78.4	60.8
Red sandstone	21.6	14.3	25.0	0.0	9.3	20.5	15.6	6.9	10.9	7.4	9.3	6.3	16.7	24.5	7.2	14.3
Chert	0.0	14.3	9.4	20.0	12.5	15.4	12.5	6.9	6.5	3.8	9.3	1.6	19.5	8.2	0.0	7.1
Quartzite	0.0	14.3	0.0	20.0	6.3	12.8	12.5	3.4	4.3	7.4	9.3	15.9	8.3	4.1	7.2	10.7
Gneiss+Igneous	24.3	0.0	18.7	20.0	12.5	7.7	0.0	13.8	6.5	11.1	14.0	6.4	11.1	2.0	7.2	7.1

TABLE 2.—*Binghamton pebble counts*
Analysis of variance

Source	Sums of Squares	d.f.	M.S.	*F*
Between segments	26.86	3	(8.95)	
Between localities within segments	38.54	4	(9.63)	
Between counts within localities	55.36	8	(6.92)	
Between types	14,327.73	4	(3,581.93)	
$S \times T$	553.57	12	46.13	<1 *NS*
$L \times T$	941.33	16	58.83	<1 *NS*
$C \times T$	2,765.49	32	86.42	
Total	18,708.88	79		

Binomial variance = 821/32 = 25.66 $F = 86.42/25.66 = 3.37^{**}$
(In this and succeeding tables *NS* = not significant; 1 star means significant at the 5% level, and 2 stars mean significant at the 1% level.)

Usually the appropriate procedure is to recompute the remaining constituents to 100 percent.

In view of the selective use of foreign pebbles, the geological questions for the Binghamton drift may be stated as follows: is the large scale (between segments) variability in foreign pebble composition demonstrably greater than the variability between localities within the segments (at the 5 percent significance level)? Is there, at the same significance level, a demonstrably greater variability in foreign pebble composition between localities than between counts at a locality? Finally, is there evidence of significant heterogeneity between counts within the localities? These questions relate to the over-all homogeneity of the drift sheet, and permit estimates to be made of the magnitude of the variations at the several sampling levels. Moreover, the method does this simultaneously, for all the constituents that are considered to be important in the particular study, providing a probability basis for a composite judgment.

Table 1 shows the Binghamton drift pebble data as recomputed percentages. The percentage in each cell was converted to its arc sine square root transformation in degrees with the table provided by Snedecor (1946, p. 449). Several condensed tables were then prepared by summing the transformed values successively over types and over the sampling levels. All the values in the several tables were squared, and by suitable subtractions seven sums of squares were broken out, as listed in table 2. Details of the computational technique, including the calculation of degrees of freedom, are given in the Appendix. The mean squares are obtained by dividing the sums of squares by the corresponding degrees of freedom.

The significance tests in table 2 are conducted with the interaction mean squares. The other mean squares are placed in parentheses to indicate that they are included for information only. In the first test the mean square for (segments × types) is divided by the (localities × types) mean square to obtain an observed *F* value less than 1. Clearly, this is smaller than the usual critical values of *F* for (12, 16) degrees of freedom (Dixon and Massey, 1951, p. 310) and the inference is that there is no evidence, at any of the usual significance levels, of greater variability between segments than between localities within a segment. One may therefore infer that the Binghamton drift sheet may be homogeneous in its foreign pebble composition, in a broad regional sense. The second test is made by dividing the (localities × types) mean square by the (counts × types) mean square. This also yields an *F* value less than 1, and there is again neither statistical evidence nor any quantitative suggestion

of a greater variability between localities than between counts at a locality.

When, as in this case, the percentages are based on counts of items (here pebbles) which might have been completely randomly mixed, a third test can be based on the known stabilization effect of the arc sine square root transformation expressed in degrees. For given sample size n, the residual variance in the transformed population has the constant value $821/n$ (Bartlett, 1947). In this illustrative example the number of foreign pebbles varied, but averaged 32 per sample. Hence the residual variance is 25.66. The ratio of the (counts × types) mean square to this value is 3.37 with $(32, \infty)$ degrees of freedom. It is highly significant (it would arise by chance in a homogeneous situation less than 1 time in a thousand). The inference from this test is that although the Binghamton drift is regionally homogeneous in a broad sense, there is a very local heterogeneity at the individual sample level which probably indicates that the foreign pebbles as a class have not travelled far enough to be uniformly mixed throughout the volume corresponding to a locality.

In some studies it may be desirable to analyze only the crystalline pebbles, which are represented by the quartzite and gneiss plus igneous rock classes in table 1. The case of two types ($m = 2$) is a special one, inasmuch as the arc sine square root transformation of the recomputed percentages always yields the fixed sum of 90.0 when only two percentages are involved. As a result the sums of squares associated with the three sampling levels are all zero, although the interaction sums of squares have nonzero values and can be treated as before. Table 3 is included as an example of this kind of analysis, where only the two crystalline classes of table 1 are used. The data were recomputed to 100 percent and transformed. As table 3 shows, the first three mean squares are zero, the mean square for types is of moderate value, and the largest mean squares are associated with the interactions. The F tests show that there is no reason to suppose, on the basis of the degrees of freedom available, that heterogeneity is present between segments, or between localities within a segment.

If only the transformed percentages of quartzite pebbles were used in the analysis, the design reduces to the univariate case in which there is no longer a between-types mean square, and no interaction mean squares. The main effects for one variable correspond to the interactions for two variables. The experiment in this case becomes a standard hierarchical design, such as was described by Olson and Potter (1954) and Potter and Olson (1954). The standard design is also described by Cochran (1953, chap. 10), Anderson and

TABLE 3.—*Binghamton crystalline pebbles*

Analysis of variance

Source	Sum of Squares	d.f.	M.S.	F
Between segments	0.00	3	(0.00)	
Between localities within segments	0.00	4	(0.00)	
Between counts within localities	0.00	8	(0.00)	
Between types	24.85	1	(24.85)	
$S \times T$	1,361.44	3	453.81	1.14 *NS*
$L \times T$	1,598.60	4	399.65	<1 *NS*
$C \times T$	15,005.41	8	1,875.68	
Total	17,990.30	31		

Binomial variance = 821/13 = 63.15 $F = 1{,}875.68/63.15 = 29.70^{**}$

TABLE 4.—*Marseilles till pebble percentages*
(Data from Anderson, 1955)

Segments	A				B				C				D			
Localities	1		2		1		2		1		2		1		2	
Counts	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Silurian	89	90	89	96	89	74	75	59	69	71	84	43	46	70	70	52
Devonian	6	1	3	0	2	10	3	13	12	7	4	19	10	8	9	21
Pennsylvanian	0	0	0	0	1	2	5	15	6	8	3	20	8	6	0	0
Limestone	8	0	4	3	3	0	2	1	4	6	3	2	28	11	8	11
Crystallines	3	9	3	1	5	12	14	12	9	8	5	16	7	5	7	14

Bancroft (1952, p. 325), and Bennett and Franklin (1954, pp. 350 ff.).

The Binghamton drift pebble illustration provides some suggestions on the design of areal studies. The similarity of test results for the upper and intermediate sampling levels in tables 2 and 3 probably results from the similarity in the average spacing at these levels. In a redesigned study the uppermost sampling level could include larger segments to give a sample spacing of about 25 miles center to center. It would probably also be advantageous to count a fixed number of foreign pebbles per sample to obtain somewhat more information per hour of counting.

A second excellent example of drift pebble distribution is provided by Anderson's study of pebble lithology in the Marseilles till sheet in Illinois (1955). The bedrock underlying the area is varied, and the till shows a strong response in pebble composition to the underlying bedrock. It was accordingly thought appropriate to include all the constituents as an illustration of a drift sheet with strong regional heterogeneity.

Figure 2 shows the sampling design laid out for the present study. The end moraine was divided into four main segments. Two localities were chosen in each segment, and two samples were selected near each locality. The samples were selected in a randomized manner from among the numerous sampling sites used by Anderson. The raw data, taken from Anderson's maps, are listed in table 4. Where necessary they were recomputed to 100% before transformation. The analysis of variance is shown in table 5.

The *F* tests indicate that there is a very significant variability between segments as compared to the variability between localities within a segment, but that the variability between localities is not significantly greater than that between samples within a locality. Comparison of the (counts×types) mean square with the stabilized residual vari-

ance shows a highly significant variability in excess of binomial.

The sample spacing in this illustration averaged about 21 miles between segments (center to center), about 12 miles between localities within the segments, and about 3.2 miles between samples (counts) at the localities. Thus in this instance the sampling levels are sufficiently different so that each embodies a different scale of areal variability.

Stratigraphic Data

This illustration using subsurface data is presented as an example related to facies studies. Five east-west tiers of townships across parts of Kansas and Oklahoma were laid out as shown in figure 3. Two blocks of 30 townships each were selected randomly in each tier, and two wells were selected randomly in each selected block. Sample logs were used to measure the thickness of sandstone, shale, and limestone in the Desmoinesian (Middle Pennsylvanian), which was completely penetrated in each of the selected wells. The design therefore has five tiers representing the major sampling segments, two blocks per tier, representing the local areas, and two wells per selected locality, representing the samples or counts. The number of types is three, representing the major lithologic components.

Table 6 shows the percentage of the three lithologic types in each well. As before, the percentages were transformed to their arc sine square root equivalents in degrees, and the completed analysis of variance is shown in table 7.

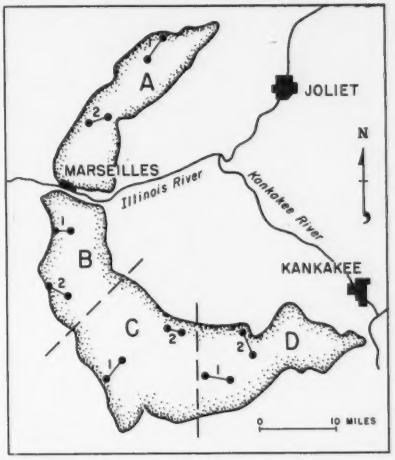


FIG. 2.—Map of Marseilles moraine, showing major segments and sample localities used in till pebble analysis. Adapted from Anderson (1955).

The F tests in this example indicate no significantly greater variability between the tiers than between the blocks of townships within the tiers. The tests suggest, however, that the variability between the blocks of townships is significantly greater than between wells within a block. This illustrates an instance in which the maximum heterogeneity appears to be related to an intermediate areal scale.

TABLE 5.—*Marseilles pebble counts*
Analysis of variance

Source	Sum of Squares	d.f.	M.S.	F
Between segments	193.29	3	(64.43)	
Between localities within segments	35.99	4	(9.00)	
Between counts within localities	48.65	8	(6.08)	
Between types	28,445.59	4	(7,111.33)	
$S \times T$	2,489.66	12	207.47	4.71**
$L \times T$	705.00	16	44.06	<1 *NS*
$C \times T$	1,587.60	32	49.61	
Total	33,505.57	79		

Binomial variance = 821/100 = 8.21 $F = 6.04^{**}$

TABLE 6.—*Desmoinesian stratigraphic data in percentages*

Tiers (Segments)	A				B				C				D				E			
Blocks (Localities)	1		2		1		2		1		2		1		2		1		2	
Wells (Samples)	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Sandstone	14.1	4.7	19.3	31.5	0	0	14.0	6.1	6.1	0	35.3	12.8	0	0	1.3	8.9	0	0	0	0
Shale	42.7	41.4	21.1	27.2	54.1	31.4	48.0	37.7	45.4	23.0	37.9	43.0	30.9	34.1	43.5	17.9	26.1	34.2	38.5	65.0
Limestone	43.2	53.9	59.6	41.3	45.9	68.6	38.0	56.2	48.5	77.0	26.8	44.2	69.1	65.9	55.2	73.2	73.9	65.8	61.5	35.0

The proportions in this example are not based on counts, and no excuse exists for the calculation of a binomial variance. (This will almost always be the case in such lithological facies studies.)

This example is included in part to illustrate a feature of the sampling design. The east-west tiers are long strips, so that the blocks of townships in the tiers can be farther apart than the center-to-center distance between tiers. In the example this latter distance is 5 townships, whereas the average distance between chosen blocks in the tiers is about 13 townships. The wells in each block average about 1.7 townships apart. Thus, unless there was a meaningful geological reason for concentrating on north-south variation, the analysis as presented suffers from an element of indefiniteness in sampling design inasmuch as the spacing does not decrease down the hierarchy. The implication is that, if no such geological motivation to tiers exists, either the largest units should be laid out as large blocks of townships with the nests within them, or cognizance should be taken of an east-west variation in contrast to a north-south variation. This point is further discussed in a later section.

Heavy Minerals in Beach Sand

This example is based on a study by Pettijohn (1931) in which the texture and

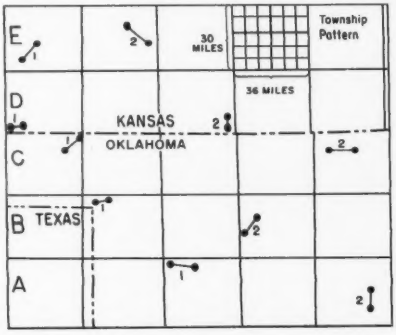


FIG. 3.—Map of parts of Kansas and Oklahoma showing location of wells used in Desmoinesian stratigraphic analysis. The number of control points used for illustration is fewer than would normally be used in such an analysis.

TABLE 7.—*Desmoinesian stratigraphic data*
Analysis of variance

Source	Sums of Squares	d.f.	M.S.	*F*
Between segments (tiers)	140.59	4	(35.15)	
Between localities (blocks) in segments	106.15	5	(21.23)	
Between wells in localities	30.02	10	(3.00)	
Between types	14,268.06	2	(7,134.03)	
$S \times T$	1,716.68	8	214.58	1.22 *NS*
$L \times T$	1,763.83	10	176.38	2.44*
$C \times T$	1,446.50	20	72.32	
Total	19,471.83	59		

heavy minerals of beach sands on the west and east shores of Lake Michigan were compared. The original design is simplified to illustrate one way in which two major populations may be contrasted. The shore was divided into two major segments as shown in figure 4, and two pairs of samples were selected from local areas in each major segment. A transitional area at the head of the lake was omitted to bring the contrast out more sharply.

Pettijohn listed some dozen heavy minerals in his study. Of these, all were included that were present in amounts 0.5 percent and greater except the "leucoxene+weathered" class. This gave seven types after some grouping of the pyroxenes and amphiboles. The percentage data used in the study are given in table 8, and the analysis of variance is shown in table 9. The tests indicate that there is a significantly greater variation between the two sides of the lake (major segments) than there is between localities on a side; and there is a highly significantly greater variation between localities on a side than there is between samples in each local area.

This study, though based on only eight samples, agrees with Pettijohn's conclusions, and affords an illustration of a common situation in which nearby samples are more homogeneous than those collected farther apart. The average distance between samples in a pair was about 6 miles, and the average distance between local areas on a side was about 16 miles.

In designing a study for contrasting two major areas, the sensitivity of the analysis is increased by using more than two localitities in each segment. The fact that, in the present instance, the presence of seven types in the analysis provided a fair number of degrees of freedom for the *F* tests may tempt the unwary to introduce additional, less geologically relevant, variables to increase degrees of freedom. The addition of less relevant variables will actually decrease sensitivity rather than increasing it, and should be carefully avoided.

DESIGN ELEMENTS FOR AREAL STUDIES

The illustrations in the preceding section afford several examples of sampling designs for the statistical model.

FIG. 4.—Southern part of Lake Michigan showing location of beach sand samples, adapted from Pettijohn (1931).

TABLE 8.—*Percentages of heavy minerals in Lake Michigan beach sands (Data from Pettijohn, 1931)*

Segment	A				B			
Locality	1		2		1		2	
Count	a	b	a	b	a	b	a	b
Garnet	3.4	5.3	6.6	5.8	26.1	19.1	20.4	12.2
Pyroxene	46.5	38.9	37.4	24.1	6.1	6.7	6.0	2.9
Amphibole	19.1	19.7	13.2	10.8	24.3	36.7	15.9	7.6
Epidote	1.7	2.5	1.1	0.8	3.4	5.5	2.2	2.4
Zircon	0.5	0.6	1.4	1.1	1.4	0.5	1.1	1.5
Tourmaline	0.0	0.0	0.0	0.0	1.4	3.7	0.9	1.0
Iron ores	28.8	33.0	40.3	57.4	37.3	27.8	53.5	72.4

Basically the plan involves selecting several sampling levels, each on a different areal scale. The scales can be set by subject matter considerations and may vary from very broad scales for regional studies to extremely detailed scales for local studies.

All of the examples included three sampling levels, although this is arbitrary. Use of two sampling levels simplifies the design and reduces the number of significance tests that can be made. Extension to four or more levels permits more detailed evaluation of very local effects, but requires computation of additional mean squares. Such extensions are mentioned in the Appendix.

The statistical model used here is appropriate to a randomized design, which assumes that the localities within segments and the samples within localities are selected by some process of randomization (coin tossing, a deck of cards, dice, or a random number table). Complete randomization may be limited by occurrence of covered intervals and by other complications. Adjustments are possible in such instances, some of which are treated by Potter and Olson (1954), Olson and Potter (1954), Potter and Siever (1955), and Krumbein and Slack (1956). Cochran, Mosteller, and Tukey (1954) discuss the question of weighting factors when probability sampling is limited. Subject matter considerations may also enter, leading to systematic or stratified sampling (Cochran, 1953). Sample stratification is desirable when several geological populations are present, as when sand lenses occur in shale, or when a beach has well developed foreshore and backshore. In some studies it may be desirable to follow parallel sampling plans in the several strata to avoid complexities arising from randomization over the entire zone.

Sampling plans in geology may be linear, areal, or three dimensional. The following subsections treat examples of studies that fall into each class.

Linear sampling plans—These apply to samples collected along an outcrop band, along a stream, along a barrier beach, along igneous dikes, or in other situations where sampling may be limited to an essentially linear pattern. Problems of sample stratification may enter, as on foreshore and backshore of a beach or in border and interior zones of a dike.

The general sampling plan divides the total length into a convenient number of major segments, preferably of equal length. Each major segment is divided into a fixed number of shorter segments (called local areas or localities here), and each of the intermediate segments is divided into a fixed number of minor segments for individual sampling sites. In the simplest plan all major segments are used, two localities are selected at random from each major segment, and two samples are selected at random in each chosen locality. This simplest scheme may be modified by taking only

some of the major units at random, and selecting more than two subunits at each lower level. In many cases the desirable balance of degrees of freedom may involve taking sometimes one and sometimes two samples from a locality (localities from a segment). This will complicate the calculations somewhat, but may produce more useful information from a given number of counts or wells.

Areal sampling plans—When samples are to be collected over an area, the simplest plan is to divide the area into major squares, and to nest the smaller units within them. Potter and Siever (1956) describe such a plan based on county-sized "supertownships" in which townships, sections, and wells were successively nested. This arrangment is very useful and may be adapted to any convenient areal scale from square feet to acres, sections, townships, and supertownships. A simpler version of this areal plan is to divide the total area into major strips, as was done with the first drift pebble example. Various methods of selecting local areas within the strips may be used. If the strips are much longer than they are wide, the number of localities in each strip may be increased to obtain an average spacing that is smaller than the inter-segment distance. An alternative is to sample several segments at random from a larger choice, to obtain a larger spacing at the top level.

Areal sampling plans include studies of sedimentary environments where a limited thickness of sediment is sampled; the study of large igneous masses, such as some batholiths; and subsurface stratigraphic studies where lithologic content is emphasized without regard to vertical placement of the rocks in the unit. This latter includes most common lithofacies studies based on percentages of sandstone, shale, limestone, evaporite, etc.

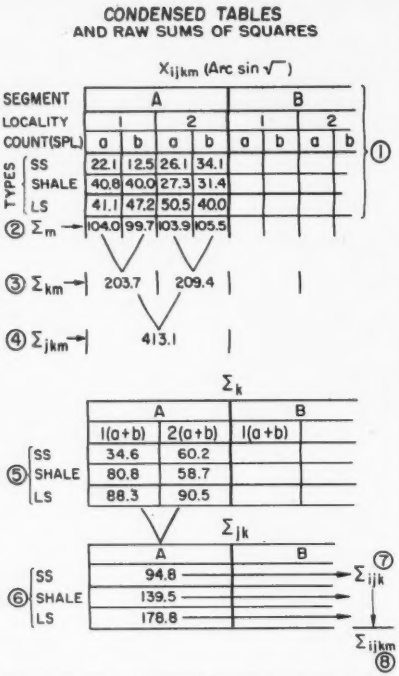
Three-dimensional sampling plans—Although study of a stratigraphic unit involves the third dimension, the present section refers to comparison of two or more rock layers in the same map area. If a simultaneous study is to be made of the Desmoinesian and Missourian in Kansas, for example, the design has to be modified to permit inclusion of an additional factor for "stratigraphic position." This additional factor introduces four more two-way interactions and three three-way interactions. Because of complexities in computation and tests this extension of the model is reserved for a subsequent study.

CONCLUDING REMARKS

The statistical model introduced here was designed specifically for a class of geological problems which arises with increasing frequency as emphasis on areal studies grows. The method not only applies to areal studies of sedimentary, igneous, and metamorphic rocks in terms of areal variation in mineralogic or chemical composition, but it appears to be equally suitable in paleontology, geomorphology, and other branches of ge-

TABLE 9.—*Lake Michigan beach sand*
Analysis of variance

Source	Sums of Squares	d.f.	M.S.	*F*
Between segments	19.68	1	(19.68)	
Between localities within segments	11.00	2	(5.50)	
Between counts within localities	3.93	4	(0.98)	
Between types	8,754.93	6	(1,459.15)	
$S \times T$	1,639.93	6	273.32	4.27*
$L \times T$	767.46	12	63.95	5.11**
$C \times T$	300.52	24	12.52	
Total	11,497.45	55		



IV: $\sum_{ijk}(\sum_{m} X_{ijkm})^2/_m$ Sum of squares of all items ②, divided by m.	D: $\sum_{ijkm}(X_{ijkm})^2$ Sum of squares of all items in ①
III: $\sum_{ij}(\sum_{km} X_{ijkm})^2/_{km}$ Sum of squares of all items ③, divided by km.	C: $\sum_{ijm}(\sum_{k} X_{ijkm})^2/_k$ Sum of squares of all items in ⑤ divided by k.
II: $\sum_{i}(\sum_{jkm} X_{ijkm})^2/_{jkm}$ Sum of squares of all items ④, divided by jkm.	B: $\sum_{im}(\sum_{jk} X_{ijkm})^2/_{jk}$ Sum of squares of all items in ⑥ divided by jk.
I: $(\sum_{ijkm} X_{ijkm})^2/_{ijkm}$ Square of grand total ⑧, divided by N = ijkm.	A: $\sum_{m}(\sum_{ijk} X_{ijkm})^2/_{ijk}$ Sum of squares of all items ⑦ divided by ijk.

ology where data are naturally assembled in terms of the percentages of several variables that add up to 100 percent.

The method appears to open a fairly large field to statistical analysis, especially inasmuch as extensions to additional factors are possible. Although the computations increase in complexity as the model is generalized, the sums of squares are always computed in ordinary univariate ways so that use of standard routines with desk calculators or of IBM equipment for large experiments is feasible.

The writers are indebted to their colleagues for discussion and selection of examples. Thanks are especially due to Dr. Paul MacClintock of Princeton University, whose friendly discussions during early stages in development of the design helped formulate the geological questions for the statistical model, to Dr. Martin B. Wilk of Princeton University for critical reading of the statistical portions of the manuscript, and to Lt. L. M. Noel for careful checking of certain calculations. Financial support from the Graduate School of Northwestern University and the Office of Naval Research is gratefully acknowledged.

APPENDIX

The statistical model illustrated in the body of the paper represents a nested sampling design crossed with the mineral or chemical constituents (types) that were measured in the samples. A general description of nested and cross-classifications for the univariate case is given in Bennett and Franklin (1954, pp. 348–426). The present design may be formally considered a two-way factorial in which one factor represents a nested geographic grouping and the other represents the types of constituents that make up a sample.

FIG. 5.—Schematic diagram for condensation of data and computation of mean squares for multivariate model. The examples are the arc sine square root transformation of the percentage data in table 6.

A similar analysis may be made whenever the constituents measured in the sample are crossed with a design, *Q*, whose analysis is well understood. For each line which would arise from single measurements according to *Q*, there will be a corresponding interaction with constituents in the design "*Q* crossed with constituents," and the understanding of the lines of *Q* can be immediately applied to these interactions. Thus, in the present model the design *Q* is a three-level nested sampling design, and for each level there is an interaction in the crossed design. The areal scale associated with each level in the *Q* design is accordingly assigned to the corresponding interaction in the crossed design.

The formal main effects (and interactions) of the variables present in *Q* can almost always be forgotten. If we had analyzed the raw percentages themselves, then, since the percentages will always total to 100 percent, these mean squares would not only be forgettable, but would vanish identically. When transformed data are analyzed, they will not vanish identically, but they are rather certain to be small, reflecting small variations in totals (across constituents) of transformed percentages. Moreover, these small variations are unlikely to have any useful interpretations.

Since the main effects (and interactions) of variables in *Q*, here the sampling levels, are both small and uninformative, the information we desire must be carried in the corresponding interactions. More careful analysis shows this to be indeed the case.

The transformation we propose is valuable for several reasons. Not only does it stabilize binomial variation, but it comes far closer to making equal scale changes of equal geological importance. It makes the change from 50 percent to 55 percent much less important than a change from 5 percent to 10 percent, but still more important than a change from 5

ANALYSIS OF VARIANCE

Source	Sum of Squares*	Degrees of Freedom	Mean Square	
BETWEEN SEGMENTS	$SS_1 = II - I$	$i-1$	$V_1 = SS_1/(i-1)$	NOT USED IN TESTS
BETWEEN LOCALITIES WITHIN SEGMENTS	$SS_2 = III - II$	$i(j-1)$	$V_2 = SS_2/i(j-1)$	
BETWEEN COUNTS (SAMPLES) WITHIN LOCALITIES	$SS_3 = IV - III$	$ij(k-1)$	$V_3 = SS_3/ij(k-1)$	
BETWEEN TYPES	$SS_4 = A - I$	$m-1$	$V_4 = SS_4/(m-1)$	
SEGMENTS X TYPES INTERACTION	$SS_5 = (I+B)-(II+A)$	$(i-1)(m-1)$	$V_5 = SS_5/(i-1)(m-1)$	
LOCALITIES X TYPES INTERACTION	$SS_6 = (II+C)-(III+B)$	$i(j-1)(m-1)$	$V_6 = SS_6/i(j-1)(m-1)$	
COUNTS X TYPES INTERACTION	$SS_7 = (III+D)-(IV+C)$	$ij(k-1)(m-1)$	$V_7 = SS_7/ij(k-1)(m-1)$	
TOTAL	$D - I$	$ijkm-1$		

* Sums of squares obtained by indicated subtractions of raw sums of squares in preceding computational chart.

FIG. 6.—General form of multivariate analysis of variance table. Compare with figure 5 for subtractions shown in second column.

percent to 6 percent. In doing so, it seems to agree, roughly, with the judgment of most careful students of percentage data.

The arrangment of the data for analysis is shown schematically in figure 5, which represents part of the arc sine transformed data of table 6. The items in each column are first added to obtain the summation over m. These are combined over counts (a and b) to obtain the summation over km, and are then combined over localities (1 and 2) to obtain the summation over jkm. A second condensed table is prepared by adding a and b for each type, to obtain a summation over the counts, k. These are next combined over localities to obtain the summation over jk. By carrying the totals to the right, summation over ijk is obtained. Finally, these latter items are added to obtain the grand total summed over $ijkm$.

The manner of computing the raw sums of squares is shown in the lower part of figure 5. As indicated, all the original items and all the sums are squared to obtain the eight numbers designated as I to IV and A to D. These numbers are then used in the analysis of variance shown in figure 6. The final sums of squares are obtained by making the subtractions indicated in the second column. The degrees of freedom are distributed as shown in the third column. It will be noted that the first three items involve only the sampling levels (i, j, and k), and the fourth item has only the types, m. The interaction degrees of freedom are distributed conventionally as the products of the d.f. for the levels and the types.

In conducting the analysis the first four mean squares are not used, and the F tests are made by taking the ratios V_5/V_6, V_6/V_7, and (if knowledge of the count size n is available), the ratio of V_7 to the stabilized variance, $821/n$. The observed F values are used to test the following statistical hypotheses:

1) The variation in over-all composition between segments is not significantly greater than the variation in over-all composition between localities in a segment at the 5 percent significance level. This test is based on V_5/V_6.
2) The variation in over-all composition between localities is not significantly greater than the variation in over-all composition between samples (counts) in a locality at the 5 percent significance level. This test is based on V_6/V_7.
3) The variation in over-all composition between counts is not significantly greater than would be present if the constituents were thoroughly "mixed" throughout the rock unit. This test is based on $V_7/(821/n)$.

Each test is conducted with the degrees of freedom associated with the ratio except the last test, which uses $[ij(k-1)(m-1), \infty]$ degrees of freedom.

Extensions of the model to include additional sampling levels requires computation of two additional raw sums of squares for each additional level. If a design is prepared using h areas, i segments per area, j localities per segment, k counts per locality, and m types per count, condensed tables are prepared of summations over k, jk, ijk, $hijk$, m, km, jkm, $ijkm$, and $hijkm$. These are squared and summed over the remaining subscripts in a manner similar to that indicated in figure 5.

Extensions of the model to include an additional factor for "stratigraphic position" involves preparation of 16 condensed tables in a three level sampling plan. The number of interactions increases from three to ten, some of which are three-way interactions. The succession of F tests also differs from the simpler model. It is felt appropriate under the circumstances to defer treatment of these generalized models to a report specifically on such a design.

A second possible extension of the model is to separate the top level of the sampling hierarchy into rows and columns. In this manner the geographic grouping has an east-west and north-south sense, which would permit sharper

distinction of directions in which nonhomogeneity extends. This more versatile model also requires computation of additional raw sums of squares and introduces additional interactions into the design. Such a composite model for the univariate case is described by Bennett and Franklin (1954, p. 411), and Krumbein (1955). It is also possible to extend the model to other standard univariate designs, such as the single factor analysis of variance design, the single-entry row-column design, and to regression designs.

The statistical model and analysis may be used to estimate variance components quantitatively. Certain precautions are necessary. Variance components for sampling levels in the crossed design have no direct interpretation whatever. The variance components for constituents (types) is greatly affected by the choice of variables and is unlikely to be a useful quantity. The variance components for interactions are meaningful, but the scale on which they are expressed is unfamiliar, so that the geologist is urged to acquire experience with their values in geologically-understood situations before using them in interpretation.

The precise probabilities obtained from the *F*-tests should be interpreted with some caution, since it is possible that the formal numbers of degrees of freedom overestimate the appropriate equivalent numbers. However, even if this occurs, the average values of the mean squares will retain the simple interpretations which have been discussed.

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FIG. 1, DECEMBER, 1956

SANDY ZONES IN THE CHATTANOOGA OF THE EASTERN HIGHLAND RIM, TENNESSEE

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ABSTRACT

Sandstone beds are more abundant than previously realized in both the Dowelltown (lower) member and the Gassaway (upper) member of the Chattanooga shale of the Eastern Highland Rim of Tennessee. Such beds increase in number and thickness from Dekalb County to the north and west toward Macon County.

A sandstone or conglomerate bed, normally present at the base of the Chattanooga shale, has been generally recognized by writers in the past. However, additional occurrences of sandstones are relatively common throughout the Dowelltown member, and many exposures contain several such beds.

A persistent sandstone bed occurs at the base of the Gassaway member of the Chattanooga over most of the Eastern and Northern Highland Rim. This bed, called the Bransford sandstone by Campbell (1946), is a useful stratigraphic marker in separating the Chattanooga into its two members.

A series of thinly laminated siltstones occur in the Gassaway member throughout the area studied. However, only a few occurrences of sandstone are known in the upper Chattanooga.

The present study suggests that these sands were deposited by relatively agitated water at shallow depths and are not lag concentrates.

This report is preliminary, and suggestions for further study are submitted.

INTRODUCTION

Geologists of the University of Tennessee have been studying the Chattanooga shale under contract for the United States Atomic Energy Commission since November 1951. This paper on sandstones in the Chattanooga shale presents some preliminary results on this aspect of the investigation. It is a progress report on work to be continued. The area of investigation includes DeKalb, Putnam, Cannon, White, Smith, Jackson, Clay, Overton, Macon, and Sumner Counties in Tennessee, and Cumberland, Monroe, and Allen Counties in Kentucky.

The writer wishes to acknowledge his indebtedness to the personnel of the project for their help in preparing this report and the geologists of the United States Geological Survey for the stimulating exchange of ideas resulting from a mutual interest in the stratigraphy of Chattanooga shale. Many of the observations used in preparing this paper were made by the writer's colleagues, R. T. Elmore, S. G. Conrad, E. G. Szmuc, and K. V. Hoover. E. E. Russell has assisted in the preparation and study of specimens. The entire program is under the valuable direction of P. B. Stockdale with H. J. Klepser supervising field investigations.

[1] Now: Tennessee Division of Geology.

PREVIOUS STUDIES

The sandstones of the Chattanooga shale have received surprisingly little attention with the exception of the one at the base. Campbell (1946, p. 884) described some and named one of them the Bransford sandstone from a Sumner County, Tennessee, exposure earlier studied by Mather (1920, pp. 19–20) and Pohl (1930, pp. 151–152). Rich (1951) described a few of the sands and concluded that they are lag concentrates of deep water origin. Klepser (1953, p. 1533) presented the views of the geologists at The University of Tennessee concerning the stratigraphy of the Chattanooga shale. Other recent studies are those of Conant (1952) and associates of the U. S. Geological Survey.

GENERAL

The Chattanooga shale is readily divisible into two units throughout the area studied. We have adopted Campbell's terms Dowelltown and Gassaway for the lower and upper units, respectively, but have modified his definitions to be regionally consistent (Klepser, 1953, p. 1533, Conant 1952, p. 1529). We are tentatively using Campbell's term "Bransford" for a sandstone which commonly occurs at the Dowelltown-Gassaway contact.

Sandstones are relatively so much more common in the Dowelltown than in the Gassaway that their presence in a partial exposure of the Chattanooga is presumptive evidence that such rocks are assignable to the Dowelltown. Local exceptions to this occur but are apparently special cases.

Stratigraphically, the sands are classified as the basal sandstone or conglomerate, the sandstones of the Dowelltown, the Bransford sandstone, and sandstones of the Gassaway. The present report discusses them in that order.

BASAL SANDSTONE

The sandstones and conglomerates that generally occur at the base of the Chattanooga formation have been called the "Hardin" sandstone (Safford and Killebrew, 1900, p. 137). We do not use this term since it is by no means certain that the type Hardin sandstone is stratigraphically or chronologically equivalent to the basal Chattanooga everywhere.

A basal sandstone or conglomerate zone has been recognized in 74 percent of 241 measured sections. Such occurrences seem independent of geographic location, although the basal sandstone is generally thicker and better developed from central Jackson County north and from eastern Clay County west than in sections south and east of these areas.

The basal sandstone ranges in thickness from a feather-edge to a unit approaching 1.0′. It consists of quartz, calcite (secondary?), pyrite (secondary?), chert fragments and nodules, bone, conodonts, vegetable shreds, teeth, and reworked Ordovician brachiopods. In some exposures this unit is chertified, presumably by reconstitution of the initially siliceous rock by ground water. In some outcrops the strike extension of the bed can be seen to grade from dense chert into a fairly friable sandstone. An interesting feature in some sections is the occurrence of a feather-edge of gray-black shale below the sandstone. In other sections the sandstone intertongues with shale for several tenths of a foot above the base, so that both shale and sandstone are locally in contact with the subjacent limestone. For example, on the Pleasant Grove Peninsula in Dale Hollow Reservoir the basal sandstone rests on the Leipers limestone, but locally the contact has a feather-edge of gray-black shale below a sandstone.

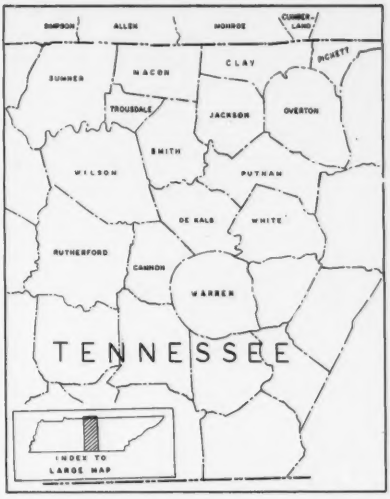

FIG. 1

SANDSTONES WITHIN THE DOWELLTOWN

Sandstones commonly occur throughout the Dowelltown member of the Chattanooga formation from central Jackson County north and west into

Macon County. They are not uncommon in DeKalb County, but are by no means as abundant as on the northern Highland Rim:

DeKalb and White Counties: 8 of 33 exposures	24 percent
Cannon County: 1 of 16 exposures	6 percent
Putnam and Smith Counties: 5 of 20 exposures	25 percent
Jackson County: 21 of 52 exposures:	40 percent
Clay and Overton Counties: 16 of 54 exposures	30 percent
Macon County: 32 of 47 exposures	68 percent
Totals 83 of 222 exposures	37 percent

The Dowelltown sandstones range in thickness from a feather-edge to 0.3′. The sands consist of fine, well-rounded, more or less frosted quartz grains with pyrite (secondary?). Some of these sandstones are the "orthoquartzites" of Pettijohn (1949, p. 237). Some are calcic, even when observed in fresh drill cores. Brachiopod shells and fragments, bone, vegetable matter, and bitumen have also been observed. The sandstones are usually intertongued along strike with black shale, and a number contain angular fragments of shale. Cross-bedding has been noted in several exposures, and graded bedding is known to occur. The exposure in McFarland Creek along the Tennessee-Kentucky line 7 miles northwest of Celina is cited for the development of these Dowelltown sandstones. No less than 5 sandstones occur here in addition to the basal sandstone and the Bransford. Ordovician brachiopod shells in a sandstone matrix occur 1.9′ above the base. Occurrences of Ordovician fossils well above the base of the shale are not uncommon:

DeKalb, White, Cannon Counties:	0 percent
Putnam County: 2 of 21 exposures	1 percent
Jackson County: 3 of 59 exposures	5.1 percent
Clay and Overton Counties: 18 of 54 exposures	33.4 percent
Macon County: 12 of 47 exposures	25.5 percent

Stratigraphically, brachiopods derived from Ordovician rocks have been noted as follows:

Basal sandstone 24 of 244 exposures	9.8 percent
Dowelltown sandstones (other than basal) 21 of 258 exposures	8.1 percent
Bransford sandstone 3 of 311 exposures	1 percent

All identifiable specimens are *Platystrophia ponderosa*, a species most abundant in the upper argillaceous facies of the Leipers formation of Maysville age. It seems significant that the areal distribution of the fossils cited above corresponds rather closely to the extent of the argillaceous facies of the Leipers.

BRANSFORD SANDSTONE

The Bransford sandstone member was named by Campbell (1946, p. 884) from an outcrop of the Chattanooga near Bransford, Sumner County, Tennessee. Campbell identified this bed at the contact of his Dowelltown and Gassaway "formations" at this and other localities in Tennessee, "west and north of the Basin."

The present work has established that a sandstone essentially like that at Bransford is present in 156 of 311 exposures at the Dowelltown-Gassaway contact from Cannon and DeKalb Counties to Monroe County, Kentucky. The distribution in Tennessee is as follows:

DeKalb and White Counties: 12 of 53 exposures	23 percent
Cannon County: 6 of 18 exposures	33 percent
Putnam and Smith Counties: 5 of 22 exposures	23 percent

Jackson County: 34 of 59 exposures	58 percent
Macon County: 28 of 35 exposures	80 percent
Clay and Overton Counties: 34 of 47 exposures	72 percent

Campbell's non-recognition of the easterly and southerly distribution is probably due to his mislocating the Gassaway-Dowelltown boundary and wide-spacing of sections.

The Bransford sandstone ranges in thickness from a feather-edge to 1.0′ and in grain-size from a siltstone to a conglomerate. It is probably best termed a subgraywacke (Pettijohn, 1949, p. 225). Invariably this bed contains abundant conodonts, and commonly contains bone fragments, vegetable remains, fragments of black shale, teeth, and quartz grains. The unit is abundantly pyritic (secondary?), with pyrite commonly replacing bone and other organic remains. The bed is cross-bedded in some exposures and in many appears to grade into fissile black shale above. Generally, it appears to be more closely related to the overlying Gassaway than to the Dowelltown member.

SANDSTONES OF THE GASSAWAY

True sandstones are rare in the upper or Gassaway member of the Chattanooga. Several thinly laminated, cross-bedded, pyritic siltstones do occur in the middle Gassaway unit as first noted by L. C. Conant. The most prominent and persistent of these beds has been termed by him the "varved" bed (Conant, personal communication). Conant thinks it is very unlikely that this bed represents a seasonal sedimentary cycle of the type varved clays of glacial deposits. The writer suggests that possibly this bed is a laminated deposit formed on a seashore, and is of the type described by W. O. Thompson (1937) in his paper on beach deposits of the present coast of California. Thompson found that the balance of deposition and removal of sediments by the incoming waves and their backwashes, respectively, where sediments of mixed specific gravities or sizes are present, results in the formation of laminated deposits. Each lamina is composed of remarkably uniform grains, but various laminae vary markedly one from another. Thompson states the California coast laminae range in thickness from one grain diameter to 1.2 inches. Such dimensions are similar to those of the laminated siltstones of the Chattanooga.

Members of the project have observed sandstones in the Gassaway at one exposure in DeKalb County, three exposures in Jackson County, and at one exposure in Cannon County.

SUMMARY AND TENTATIVE CONCLUSIONS

1. Sandstones are much more common in the Dowelltown member of the Chattanooga shale than is generally realized.

2. Individual sandstones are not traceable over very large areas except for the "Bransford" sandstones and the basal sand.

3. The occurrence of *Platystrophia* in many of the sandstones suggests that some of the materials were derived from nearby Ordovician rocks (Leipers) which were sufficiently elevated in Chattanooga time to be eroded.

4. Rubey (1930, p. 165) states that, " . . . the conditions most favorable for the formation and preservation of calcium carbonate, organic matter, and pyrite together would be relatively shallow water and a rapid rate of accumulation and burial of organic matter." The sandstones of the Chattanooga formation could well have been formed in a similar environment.

5. The writer does not believe that these sandstones are lag concentrates for these reasons:

   (a) Lack of coarse material in the black shale proper.
   (b) The intertonguing shale-sandstone relations at many exposures.

(c) The presence of *Platystrophia* (reworked) and black shale fragments in many sandstones.
(d) Local distribution of given sandstones, rather than considerable areal extent.
(e) Cross-bedding.
(f) Mode of occurrence, thickness, and relations of the sandstones to the enclosing shale in many cases are better explained as deposition under slightly agitated conditions.

6. It is suggested that these sandstones were water-laid, under agitated conditions resulting from currents or relatively sizeable waves.

7. The source for these materials is not clear at this time; presumably it lay to the west of the Eastern Highland Rim. There appears to be a rather close correlation between the sandstones of the Chattanooga and the underlying Ordovician rocks. The Chattanooga exposures in Macon County, for example, rest upon the Richmond group, and arenaceous rocks of Silurian age, and are the most sandy whereas the Chattanooga in Cannon County is commonly in contact with the Catheys limestone, and sands are sparse. The relationship to the upper argillaceous facies of the Leipers was noted above. Laboratory examinations of these limestones indicate that the highest percentage of insolubles occur in the Silurian, Richmond, Leipers, and Catheys in that order. Indeed, beds of quartz sand as thick as a foot have been observed in exposures of Richmond age in Macon County, and much thicker sands occur in the Laurel formation of Silurian age. The writer therefore suggests that much of the sand in the Chattanooga comes from the upper Leipers, the Richmond, and Laurel formations.

FURTHER STUDY

The source area for the sandy materials is unknown. It seems improbable that the subjacent Ordovician formations could have supplied all of the quartz. However, a study of the insoluble residues from these rocks and comparison with the Chattanooga sandstones is suggested. A sandstone bed as thick as one foot has been observed in the Richmond of Macon County. Further study may reveal other such beds.

Extension of the area of study west and north of that covered in this report with attention to the sandy zones is also suggested.

Finally, the sandstones themselves should be studied in thin section and by sedimentary and heavy mineral analyses.

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FIGS. 1–3, PLATES 1–3, DECEMBER, 1956

SEDIMENTARY STRUCTURES IN THE UPPER CARBONIFEROUS OF NORTH AND CENTRAL DERBYSHIRE, ENGLAND

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ABSTRACT

Coarse siltstones and sandstones recovered from a series of borehole cores in the Upper Millstone Grit and Lower Coal Measures of Derbyshire exhibit a variety of minor sedimentary structures. The least common show affinities with wash-outs and were probably caused by subsurface water flow. More widespread geographically and stratigraphically are contorted structures in fine-grained sandstones which have originated in some cases by penecontemporaneous flow down shallow submarine slopes and in others by secondary load-casting adjustment or possibly rilling. Associated with the above are two further types of phenomena which consist of infilled, near-vertical tubes. The smaller, with uniform diameters of 1 mm to 4 mm have been ascribed to annelid borings, whereas the origin of the larger, with their irregular morphology are more doubtful although they have been provisionally ascribed to molluscan activities.

INTRODUCTION

A systematic and complete petrological study of the sediments exposed in a series of cores from deep and shallow borings in northern and central Derbyshire, England, (fig. 1) illustrate the development of a variety of sedimentary structures hitherto undescribed. Initially they were all recorded from one core at Smeekley Wood, 7 miles south-west of Sheffield (National Grid 43/298765), but subsequently similar phenomena have been studied from an area further south in the Clay Cross neighborhood. The sediments include structures some of which exhibit affinities with wash-out action, others illustrate contortion effects, and a third group are representative of presumed action by organisms.

The stratigraphical range of the 1000 feet of strata involved in the investigation occurs between the base of the Chatsworth Grit in the local Millstone Grit succession and the top of the *Anthraconaia lenisulcata* zone of the Lower Coal Measures (fig. 2). Lithologically the strata consist of false-bedded sub-greywackes and quartzites (Pettijohn, 1949) together with thin coals, fireclays, laminated siltstones, and shales. The latter carry well-defined marine and non-marine horizons characterized by goniatites (*Gastrioceras subcrenatum* (Schlotheim), etc.) and non-marine lamellibranchs (*Carbonicola sp.*, *Anthraconauta sp.*, etc). respectively. Eden (1954, p. 81) recognized the presence of seven cyclothemic units in the Lower Coal Measures, the base of each unit taken either at a marine band, coal seam, or fireclay. At least three similar units can be identified in the underlying Millstone Grit. Thus the total range of the succession from which these structures are described comprises some ten cyclothemic units. No limestones are present within the succession.

SEDIMENTARY STRUCTURES

The evidence presented below regarding the structures is only part of the sum total collated in the petrological study of the sediments, and as such it acts as a confirmatory check on the evidence of sedimentation suggested by other methods of investigation. For the present purpose they have been systematically grouped as follows:

1. Structures showing affinities with wash-out action.

2. Structures resulting in contorted bedding:
   a. Flow-casts
   b. Load-casts
   c. Parallel load-casts or rills.
3. Structures due to organic activities:
   a. Worm borings
   b. Possible molluscan borings.

In nearly all cases a simple method of acquiring a three-dimensional picture of the structures was adopted. Serial sections were made by taking slices from a suitable specimen at selected intervals. Usually this was done at right angles to the general trend of the structure concerned if determinable, but cuts could naturally have been made at any desired angle. The major features thus obtained were traced directly onto a rigid transparent medium such as xylonite, and the plastic strips, all of uniform size and accurately orientated, were then reassembled in a holder so designed that the correct spacing was preserved. Using tints and having a strong source of transmitted light the morphology was at once apparent.

Structures Showing Affinities with Wash-out Action

These occur within a 7 feet thick carbonaceous sub-greywacke bed which rests on a thin coal seam immediately above the Chatsworth Grit at Smeekley Wood (fig. 2); their presence has not been observed elsewhere. The fresh rock, which consists of quartz (55 percent) and acid feldspars (4 percent) in a matrix (41 percent) of micas (muscovite, sericite, hydrobiotite), carbonaceous matter, calcite, ankerite, chalcedonic silica,

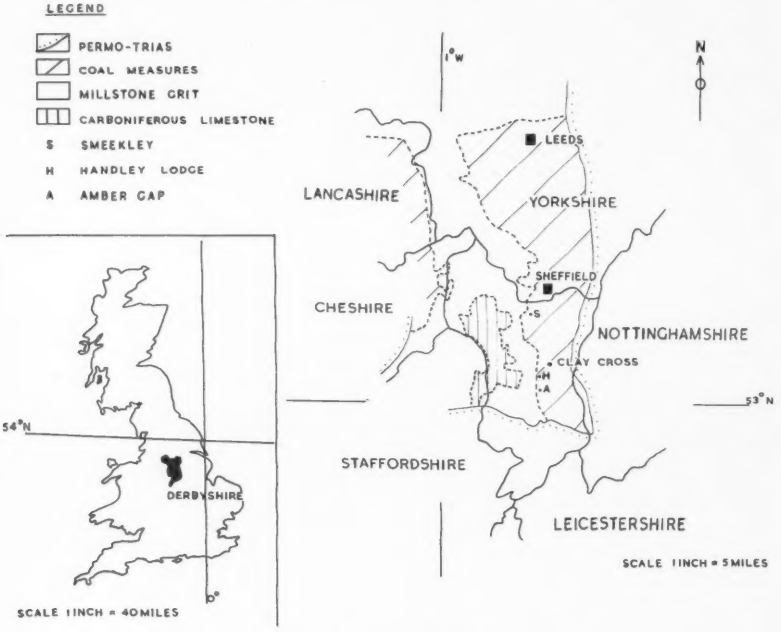

FIG. 1.—Location of boreholes.

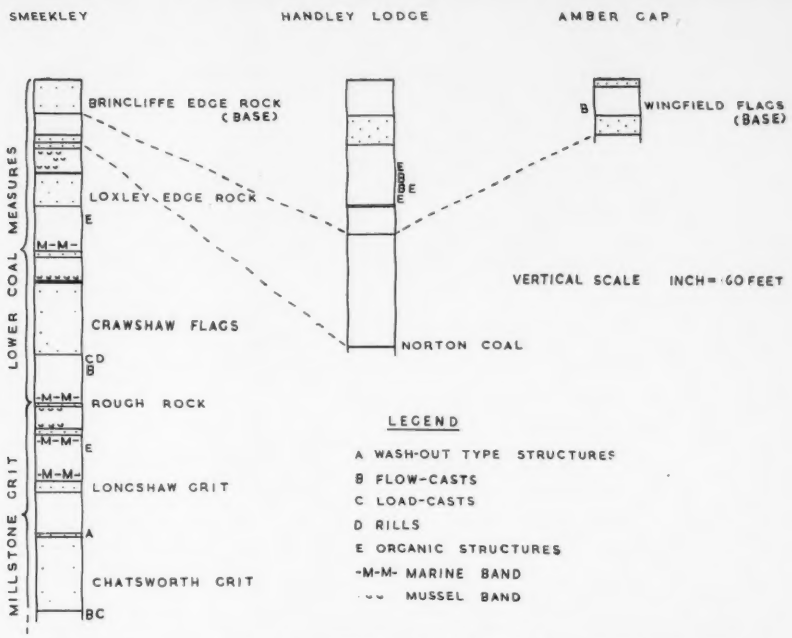

FIG. 2.—Broad correlation of localities and main horizons of structure development.

and kaolinite, is medium- to dark-grey and in this respect is unique among the sandstones of the cores studied. It is only on fresh surfaces that the lighter grey structures are prominent; all indications are lost during subsequent weathering. They may represent wash-out action, the evidence for which is common in the Upper Carboniferous rocks of Britain, but there is certain evidence which militates against their reference to the more typical and simply explained wash-out origin.

The structures exhibit a form which is generally inverted conical in cross-section and with irregular taper from top to bottom (plate 1, figs. 1 and 2). From a total of twenty observed examples, about three-quarters exhibit this form. The tapered base is well rounded while the upper surface is usually unevenly convex upwards. The physical dimensions vary considerably, but the largest structure in cross-section has a height of 50 mm with a maximum width of 38 mm at the top tapering to a minimum width of 10 mm at the base. The structures have been traced laterally through a bed for a distance of as much as 15 cm where they may terminate abruptly at a point coinciding with their maximum height, as though at the end of a trough. Alternatively, the structures may gradually become smaller and fade out. During this lateral transition, although the cross-sectional shape fluctuates, it nevertheless conforms to the general basic form. In many instances complexities arise due to the "splitting" of one structure into two with divergence of the separated forms to two distinct levels within the bed. A random section taken

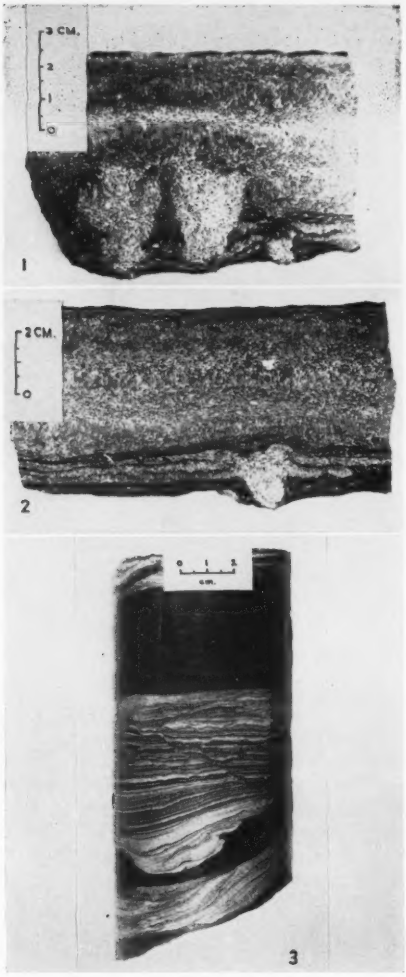

PLATE 1

FIG. 1.—The high height/width ratio and the distortion of the carbonaceous films is characteristic of these structures. The two larger structures are unified laterally into one and here have just completed their initial divergence.

FIG. 2.—Illustrates the truncation of carbonaceous films and their subsequent compaction around a typical structure.

FIG. 3.—Note the irregular base of the structure and the truncated top with superincumbent, thin, unlaminated siltstone. The movement has been approximately from right to left with thrusting of the top right siltstone over the bottom left. A thrust plane runs diagonally across the face of the laminated zone from top left to bottom right and is intersected by a similar fault towards the top left margin.

across such a divided structure might lead to an interpretation based upon two periods of genesis, whereas from consideration of the entire structure it is clear that there is only one such period. In no case has a more than bipartite divergence been observed.

Within the sandstone bed the majority of the structures are found in the upper 35 to 45 cms, such a position coinciding with a prevalence of carbonaceous laminae which are generally absent nearer the base of the bed. Where these thin, persistent laminae abut against the structures there is often abrupt truncation; yet other laminae may show either upward or downward bending suggestive of compaction later than the formative period of the structures and probably later than the cementation of the material within the structures. Although the carbonaceous matter emphasizes the external morphology, there is evidence that the petrographic dissimilarity between the structures and the surrounding rock is not so clearly confined by this common bounding material. A few of the structures have lateral, horizontal off-shoots up to 25 mm in length interdigitated between the carbonaceous laminae.

There is considerable mineralogical contrast between the structures and the surrounding sediment as illustrated by table 1. The precise origin of these structures is doubtful, but their general form and petrography point towards a genesis involving wash-out action operating either during very shallow water conditions or accompanying periods of uplift. Such an interpretation requires the rock to have been at least partially consolidated, although not compressed, in order that the formation of a trough capable of being infilled by a better sorted sediment should follow. This suggested explanation does not solve either the problem of the high height/width ratio or the divergence to two different levels. Wash-outs in the Upper Carboniferous strata of Britain, apart from occurring on a much larger scale, invariably have a low height/width ratio. Characteristically there is also a petrographic continuity of the sediment infilling the wash-out feature and the overlying, more laterally extensive sediment; yet this does not apply to the smaller structures described above. Bearing the facts in mind, it is considered probably that the genesis is a result of the flow of sub-surface water while the sediment is in a plastic state. The principle of dilatancy as discussed by Mead (1925) in regard to its geological application to unconsolidaated sediments may be fundamentally important in this respect. Dilatation involves the expansion and deformation of granular aggregates due to the rearrangement of grains mobilized by the presence of water in amounts greater than that normally within the rigid rock. A transitional loss in rigidity is thus incurred, and this would account for the looser packing of the grains within the structures, the winnowing-out of the grains smaller than 0.06 mm in size, and carbonaceous matter together with the divergence phenomenon and marginal interdigitation. The resulting rock type

TABLE 1.—*Mineralogical and textural contrast between material within structures and surrounding sediment*

Within structure	*External to structure*
1. Carbonaceous matter absent or rare. If present, well disseminated in discrete amounts.	Carbonaceous matter abundant. Commonly concentrated into thin bands.
2. Carbonates abundant; mainly calcite with a little ankerite ($\omega = 1.698$).	Carbonates not abundant.
3. Quartz and feldspar grains of less than 0.06 mm in diameter rare—about 2 percent.	Grains of less than 0.06 mm common—about 25 percent.
4. Sorting good; median grain size 0.42 mm	Sorting poor; median grain size 0.10 mm
5. Relatively open packing of clastic grains.	Closer packing of clastic grains.

has the nature of a "cleaned" subgreywacke (Pettijohn 1949, p. 243). Nevertheless, this mechanism does not satisfactorily explain either the highly individual cross-sectional form of the structures or the abrupt trough-like terminations observed. Until further data are accumulated it seems unlikely that the problem of genesis can be more fully resolved.

The general form, the horizontality, and the coarseness of the material suggests that formation was not by boring organisms.

Structures Resulting in Contorted Bedding

Included within this group heading are structures which show certain similarities in form and which possibly have a closely related genesis. There would appear to be some environmental significance in the fact that these structures are confined to laminated fine-grained sandstone or coarse-grained siltstone beds in every case, the average median diameter of the clastic grains (mainly quartz) being 0.06 mm. Plant debris sometimes occurs, but the lamination is generally controlled by variations in carbonaceous content and cementing materials (siderite, limonite, calcite, kaolinite, chalcedonic silica, and quartz) together with minor fluctuations in grain size. There is no evidence of looser granular packing within the laminae as compared with the associated structures. In the sequence of strata described here the laminated beds form about 16 percent of the Millstone Grit and about 13 percent of the Lower Coal Measures and usually exhibit either one or more of the structural developments described below.

Flow-casts

The predominating structures have marked similarity with flow-casts (Shrock 1948, pp. 156–161) and contain distinct evidence of internal flow together with a well-defined plane of truncation marking their uppermost surfaces. The best example was that which occurred at a depth of 271 feet in the Handley Lodge boring (fig. 1 and plate 1, fig. 3). Within the limits of the 7 cm core the contorted zone, interbedded between disturbed and more carbonaceous siltstone, varies in thickness from 30 mm to 50 mm. The laminae are contorted into irregular folds particularly towards the base of the structure, and small internal overthrusts suggestive of lateral movement are evident. A significant feature is the truncated top overlain by a thin, less carbonaceous, unlaminated siltstone. This junction is not considered to be a slip plane. Its presence indicates that the chronological sedimentation sequence was first a movement of the partially lithified laminated sandstones with concomitant folding and thrusting followed by deposition of the discordant, superincumbent layer. The movement, in a semi-consolidated state, seems to have been over a short distance only, of the order of millimeters, and thus hardly conducive to the destruction of the lamination. These penecontemporaneous structures possibly developed by movement down shallow slopes near the outer margins of deltas where foreset and bottom set beds intertongue. In this respect Cooper (1943, pp. 198–203) has shown that movement can be initiated on slopes as low as 2 degrees. Cooper further suggested that providing the bodies are sufficiently coherent there will be no erosion at the base of the structure especially if the underlying sediment is more plastic because of differences in mineralogy. This condition appears directly applicable to the Upper Carboniferous sediments considered here where the lower, subjacent siltstone is always more quantitatively and uniformly carbonaceous. Although there is no evidence of erosion at the base, the term flow-cast is still considered suitably descriptive for the structures. Upon cessation of sediment movement in the case of the Handley Lodge example a succeeding current truncated the uppermost surface thereby throwing the eroded sediment into suspension. This was later partially

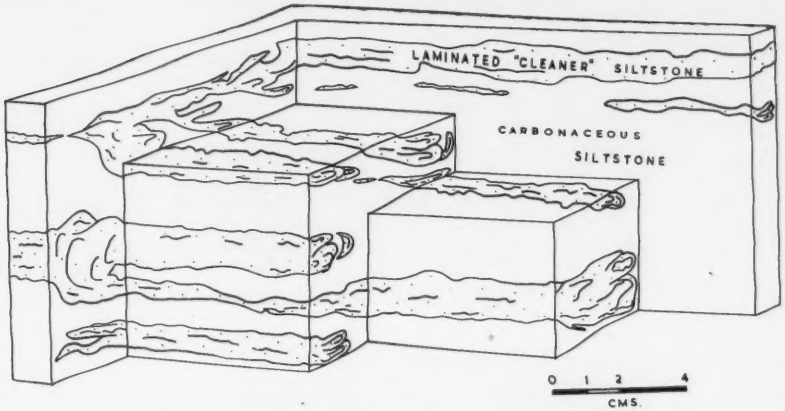

FIG. 3.—Dissection of typical flow-cast (based on tracings).

redeposited on the erosion surface as the thin (3 to 6 mm) unlaminated zone. However, not all the structures examined in Derbyshire show a "cleaned" siltstone resting on the truncated surface and in some instances the upper discordace is relatively obscure.

At 495 feet and 900 feet in the Smeekley core the structures are smaller in size, show little internal faulting, and exhibit the beginnings of a spiral or "balled" form, but there is little doubt that a similar origin is involved (fig. 3 and plate 2, fig. 1). Likewise with the largest partial structure of this type found in the Amber Gap core (figs. 1 and 2). In this case, small scale compaction faults with displacements up to 10 mm margined the structure.

According to Hadding (1931, p. 377) slides or slumps may be due to several causes. An amassing of detritus on the higher shoreward part of a slope plus differential and continually increasing weight may eventually lead to a slide. External impulses such as earth tremors or strong currents may also "trigger off" movements. The earth tremor hypothesis is advocated by Shirley (1955) for large scale contorted masses occurring at a restricted but widespread horizon in the Middle Coal Measures of the East Pennine Coalfield. If this hypothesis is applied to the minor structures described above it follows that sedimentation in Upper Carboniferous times was affected by a series of such disturbances. In view of the relatively small size of the structures and their wide areal and stratigraphic distribution, it is considered more probable that movement occurred under the dominant influence of differential loading. It is envisaged that this loading was a co-depositional effect and movements were penecontemporaneous while the sediment was still in contact with the medium of deposition. This conflicts with the secondary origin postulated by Hudson and Dunnington (1940) for structures of similar morphology developed in the Elland Flags (top of the *Anthraconaia lenisulcata* zone) of the Leeds area. Contortion in that case probably took place subsequently under a considerable load of sediments.

Load-casts

Frequently associated with the above flow structures are others of smaller size and of more debatable origin. The most common variety possesses the external morphology of a lobe *i.e.*, a slightly laterally elongated, downward projection of siltstone with a globose cross-section

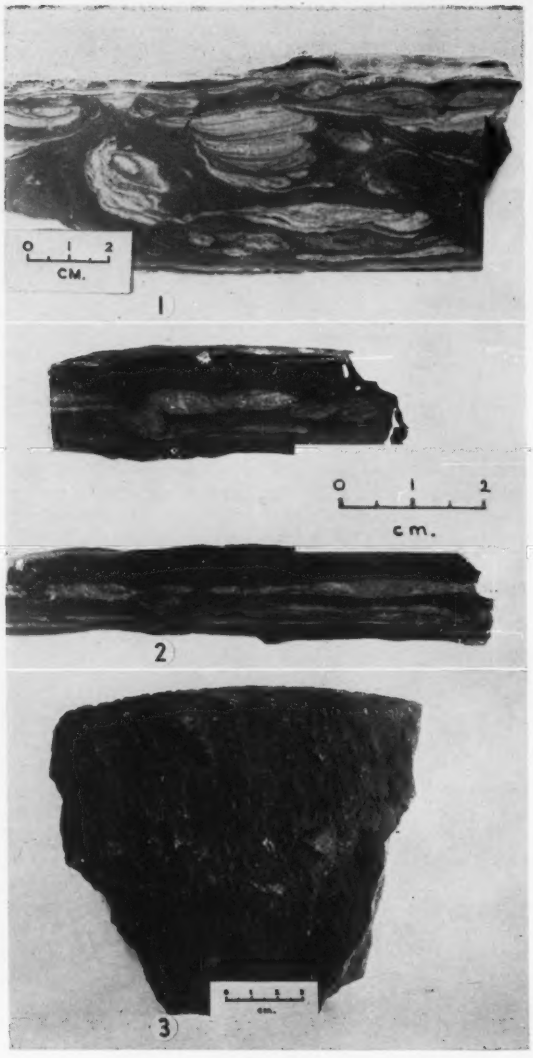

PLATE 2

FIG. 1.—Illustrates the development of a spiral or "balled" form. The truncation of the top surface is more ill-defined.

FIG. 2.—Lobes. Note the overlying depression and the irregular nature of the laminae.

FIG. 3.—The underside of a bedding plane with regular orientation of the minor structures. The larger irregular structures are probably due to the activities of organisms.

(plate 2, fig. 2). Slight variations on this basic form occur, particularly with regard to cross-section, but these are probably a reflection on such factors as the chemical and mineralogical composition and grain packing of the associated laminae. The lobes may be circular in plan view but more often show elongation in one direction although there is never any suggestion of preferred orientation. An average size for these structures is 1 cm width by 1 cm depth by 1.5 cm length, and they are usually produced by a relative displacement of a carbonaceous-poor siltstone lamina downwards into a finer grained carbonaecous-rich siltstone lamina. A shallow depression in the bedding plane above the structure is a common but not invariable result of this movement. These do not resemble pit and mound structures, bubble pits, rain pits, or vermiform markings. Neither is there any evidence that the lobes represent infilled mud-cracks.

Usually there is attenuation of the siltstone at the top of the structure where it adjoins its parent lamina; this is suggestive of adjustment under near-vertical load. Where the lobes do not have any depression immediately above it is possible that there was a compensatory lateral flowage inwards of the silt during the formative period.

Rarer types of lobes are those which are completely isolated from the parent lamina. They probably represent the final stage of readjustment.

Petrographic examination shows that the main difference between the material within the parent laminae, their associated lobes, and the surrounding rock is one of grain size allied to variation in the amount of carbonaceous matter and limonite cement. Many lobes have limonite as the dominant cementing material for the sub-angular quartz and plagioclase grains. The form and distribution of the lobate structures is determined by the presence of finer grained, more carbonaceous patches in the immediately underlying medium grained siltstone laminae. These were presumably small areas of weakness offering greater ease of penetration to the overlying cleaner silt. It is significant that in the infilling of lobe depressions there is commonly a lack of clastic mica orientation whereas laterally the long axes invariably parallel the bedding. This loss of orientation could be a purely depositional or compaction effect after the structures had been formed, although it seems reasonable to suggest that under such circumstances the parallelism of the micas to the top border of the structures would have been preserved in some cases. A post-depositional adjustment of the micaceous, carbonaceous siltstone incidental to compaction is probably a more adequate explanation.

In view of the above observations it is probable that these globose structures are secondary and a direct result of vertical loading which has involved the partial squeezing downwards of a sandstone lamina into a more plastic, finer grained, carbonaceous lamina. This effect could be defined as load-casting in contrast to flow-casting.

Parallel load-casts or rills

The smallest structures were only observed at one horizon in the Smeekley Wood core (fig. 2) and have not been noted elsewhere. They were found at a depth of 480 feet and form a series of minute protuberances on the underside of bedding planes of thin sandstone laminae (plate 2, fig. 3). They average 3 mm in length by 1 mm in width by 0.1 mm in depth and are approximately oval in plan view although there is a distinct tendency towards a triangular shape (narrow base, other sides equal) in many cases. They are slightly conical to bulbous downwards. A count along a bedding plane shows that 85 percent have a common orientation of the long axes within an arc of 5 degrees. Of the remainder, the majority have no elongation at all. It is significant that the trend of these structures is generally at right

angles to the fore-set dip of the minor current bedding developed within the sandstone.

Petrographically, the structures consist of a fine-grained carbonaceous sand stone (median diameters about 0.067 mm) with limonite the dominant cement. They are developed where the relatively coarse material of a superjacent sandstone lamina protrudes downwards into an underlying finer grained, more carbonaceous lamina. Most are continuous with the immediately overlying lamina yet others appear to be independent of it and have interspersed a very fine carbonaceous parting. Sporadic muscovite flakes occurring internally lose their general parallel and horizontal orientation as compared with those in the parent lamina and this suggests flowage as in flow-casting or load-casting. Although the protuberances may be miniature casts of that type, it is difficult to explain their regular orientation unless the immediately underlying sediment had some control. This control, if any, is not apparent in thin section. Another possibility is that they are rill marks caused by water flowing in one direction and excavating moat-like depressions around an obstacle such as a quartz grain. The hollows thus formed would be infilled subsequently by the overlying sediment. This type of rill mark is well-developed on a much larger scale in the Devonian Portage Beds of New York and in the Pennsylvanian sandstones of Indiana (Shrock, 1948). The regularity in trend militates against an origin by the activities of boring organisms.

Structures Due to Organic Activities

Often recorded from Upper Carboniferous cores and sections are structures referred to worm tubes or borings. The Derbyshire cores are no exception and show evidence of sediment disturbance at many horizons. Although there is little doubt that this disturbance was caused by the action of burrowing creatures, there is much doubt as to the exact nature of the creatures responsible since no identifiable parts remain. Nevertheless, to students of sedimentation, it is essential that fossil structures of this type should be described in detail. They occur, without exception, in laminated beds consisting of fine grained sandstone (median grain size about 0.064 mm) which alternates with more highly carbonaceous siltstone. The lighter grey, more sandy bands are often false-bedded on a minor scale, this being particularly evident where their thickness is greater than 10 mm. The bands are lenticular and the more carbonaceous laminae vary in thickness over short distances (5–15 cm) from 0.1 mm to 15 mm.

The presumed organic structures fall into two categories which are referred to (a) worm borings, and (b) possible molluscan borings.

Worm borings

The structures consist of vertical to almost horizontal tubes which extend downwards as much as 20 mm with a relatively constant diameter throughout and terminate in a well-rounded semicircular base (plate 3, figs. 1, 2). All the tubes commence vertically or slightly off vertical before they develop any later oblique trend or become parallel to the bedding. In no case do the tubes exhibit a U-shape characteristic of *Arenicolites* (Bather, 1924; Stather, 1924). Neither are they similar to the U-shape of fossil burrows occurring in the Lancashire Coal Measures which were caused by the action of the organism *Arenicola carbonaria* Binney (Binney 1852). The ratio of length to maximum diameter varies from 5 to 1 to 10 to 1, while the circular or oval cross-sections possess diameters of 1 mm to 4 mm. The composite nature of the infilling is indicated by a series of concentric zones alternately rich and poor in carbonaceous matter, but there are a few instances of non-composite sandstone infilling. The sandstone invariably consists of subangular to angular quartz grains and

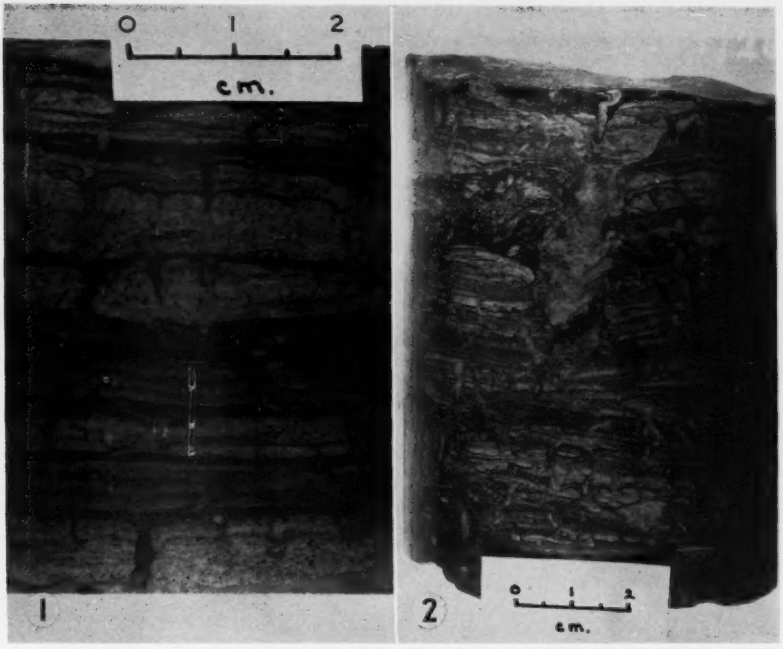

PLATE 3

FIG. 1.—Sectional view of structures probably formed by worm boring action.
FIG. 2.—The top center of the core section shows the structure probably formed by the boring activity of a mollusc. The other structures present are similar to those in figure 1.

relatively fresh acid feldspars although the latter are never present in amounts greater than 3 percent. In this respect it differs in no way from that in the surrounding laminated strata. Calcite, limonite, chalcedonic silica, and quartz are the cementing agents, and small carbonaceous fragments less than 0.2 mm in size may be sporadically distributed. It is significant that most of these carbonaceous fragments differ from those in the adjacent laminae in being smaller and well-rounded which suggests either passage through the gut of the organism or subsequent erosion of a more highly carbonaceous lamina. The tubes, with an average areal density of two per square centimeter, commence in the carbonaceous laminae which indicates increased activity of the burrowing organisms during times of quieter deposition represented by these deposits as opposed to the turbulent conditions of sandstone deposition. During the latter conditions the organisms probably either died off or migrated to a more suitable locality. A similar hypothesis was suggested for larger tubes of different morphology occurring in the Giffnock Sandstones (Upper Carboniferous) of Scotland (Macnair 1900).

Where a number of carbonaceous films are preserved within the tubes they are usually concave upwards and are independent of the laminae surrounding the tubes. Therefore, infilling probably

took place after the migration of the organism. It has been shown that modern annelids have the power to secrete an agglutinating slime capable of fixing sand grains together and vacated burrows may remain open until other material can be washed in. On this evidence together with the facts that modern annelid tubes may be less than 30 mm long, may have a vertical orientation, and are often cylindrical, it appears most likely that these Upper Carboniferous structures of like morphology have a similar origin.

Possible molluscan borings

These structures are much less common and consist of almost vertical tubes with an average length to diameter ratio of 4 to 1 (plate 3, fig. 2). The maximum length observed is 44 mm and the maximum diameter 11 mm. Although they truncate the surrounding laminae, the margins of the tubes tend to be indistinct due to intertonguing, and the more carbonaceous laminae of the surrounds usually continue in attenuated and downturned form within the structure. This suggests progressive infilling of the vacuity left by an organism which was slowly migrating upwards and keeping within the zone of active sedimentation. The infilling, consisting of "cleaner" sandstone (subangular quartz and feldspar grains and small carbonaceous fragments mainly cemented by limonite and quartz) may have been derived from the vacuity surrounds or from above by the downward movement of material between the body of the organism and the tube walls.

There is no gradation in size or morphology between these structures and the types referred to worm borings as one may have expected if they were due to the same species of organism. Thus, it seems unlikely that they are fossil analogues of modern annelid borings. It is possible that the present examples represent a transitory disturbance by lamellibranchs which normally prefer muddier waters, but the paucity of fossil evidence obviously prevents the confirmation of this.

SUMMARY

The evidence presented by the above phenomena strongly indicates that sedimentation during a part of the Upper Carboniferous in North and Central Derbyshire occurred under relatively shallow water conditions. In this it substantiates the more obvious megascopic evidence of current bedding which is widespread in the coarser sandstone beds. The presence of miniature structures resembling wash-outs implies subaerial or near sub-aerial conditions with sub-surface drainage. The contorted bedding structures in certain cases were probably due to slight movement down irregularities on the sea floor during periods of low current velocity and they may have been instigated by differential loading. Others, of lobate morphology, were probably caused by vertical loading and compression after the sediments had been removed from contact with the depositional medium. In all cases it is quite clear that more comparative and conclusive genetic data are required not only from fossil sediments of differing ages but also from recent sediments.

ACKNOWLEDGMENTS

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 4, PP. 356–362
FIG. 1, DECEMBER, 1956

HEAVY-MINERAL SUITES IN UNCONSOLIDATED PALEOCENE AND YOUNGER SANDS, WESTERN TENNESSEE[1]

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ABSTRACT

Heavy-mineral suites from unconsolidated sands of Wilcox and Claiborne age (Eocene) in the subsurface of western Tennessee were tabulated and compared with heavy-mineral suites obtained from outcropping sands known to be of Midway (Paleocene) and Wilcox age and younger.

In the subsurface at Memphis, both pink and colorless garnet are relatively abundant in the Claiborne but rare in the Wilcox. Garnet, however, is very rare in both the Claiborne and the Wilcox in the subsurface 35 miles northeast of Memphis. The mineral is very rare also in the terrace sands of western Tennessee and in samples of the Pliocene(?) and Pleistocene deposits of the Tennessee River in eastern and western Tennessee. It is possible, therefore, that the relative abundance of the mineral garnet is related to the quantity of sediment received from differing source areas in Wilcox and Claiborne times, but that, owing to the shifting of the axis of the embayment, no one source area furnished all the sediment for any formation.

Heavy-mineral suites from Pliocene(?) and Pleistocene terrace deposits of the Tennessee River in both eastern and western Tennessee, and heavy-mineral suites from Pliocene(?) deposits of the Mississippi River are much alike, and the only isotropic mineral noted in these sediments was a very rare green mineral.

Heavy-mineral suites from Recent deposits of the Mississippi River at Memphis and reported heavy-mineral suites from Cambrian sandstones of Wisconsin and Minnesota differ greatly from heavy-mineral suites of Pliocene(?) terrace deposits of the Tennessee and Mississippi Rivers and include much pink and colorless garnet. The possibility, therefore, is suggested that the Pliocene(?) terrace deposits of the Mississippi River in western Tennessee were derived largely from the basin of the Tennessee River.

INTRODUCTION

Western Tennessee is that part of the state between the Tennessee and Mississippi Rivers. It is in the northern part of the Mississippi Embayment of the Gulf Coastal Plain. In this area clays and sands of Paleocene and Eocene age (fig. 1 and table 1) crop out in continuous belts from the Mississippi to the Kentucky state lines and occupy roughly the western two-thirds of the province. These early Tertiary deposits are covered in many places by terrace deposits of sand and gravel which may be of Pleistocene age or older, and all older deposits are covered in turn by a loessial blanket of Pleistocene age.

Because of this cover of terrace deposits and loess, detailed study is necessary to locate the outcropping edges of the sands and clays which are known to dip to the west and are encountered by the drill in the subsurface of the extreme western part of the state.

As a means of locating the outcropping sands of the Claiborne and Wilcox groups of western Tennessee, a study of the heavy minerals of sands of the subsurface and of the probable outcrop area of these formations was undertaken.

Well cuttings obtained during the process of rotary drilling provided samples from the subsurface in the Memphis area and one well 35 miles northeast of Memphis. The samples were collected with great care by the writer and other geologists while the wells were being drilled. Claiborne samples came from depths of 250 to 1000 feet; Wilcox samples came from depths of 1200 to 1400 feet. Sands

[1] Prepared as a part of the ground-water studies in cooperation with the Tennessee Division of Geology. Publication authorized by the Director, U. S. Geological Survey.

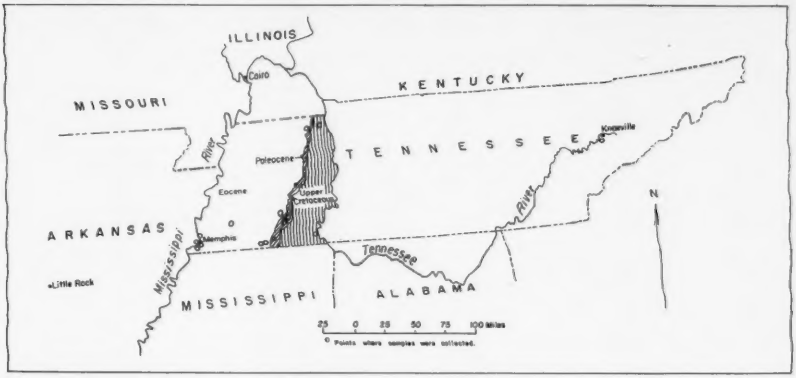

FIG. 1.—Western Tennessee and adjacent areas, and generalized geology in western Tennessee.

from the Eocene Jackson(?) formation and the Pliocene(?) terrace deposits contaminated somewhat the samples of the Claiborne, and sands from the Eocene Claiborne group and Jackson(?) formation and from the Pliocene(?) terrace deposits contaminated the samples of the Wilcox. However, since heavy minerals generally constitute only about 1 to 2 percent by volume of the sands in which they occur, it was assumed that heavy-mineral contamination of the samples used was negligible.

Various separates were studied in order to discover the representative heavy-mineral suites. Each grain of the entire heavy-mineral separate 2C (table 2) was identified, but only a split portion of each of the other separates was identified and counted. Heavy minerals from only the $\frac{1}{2}$ to $\frac{1}{4}$ mm grades were counted as sample 3C.

All the samples, unless it is stated otherwise, were separated into standard grade sizes with a sieve shaker or a small hand sieve, and only the $\frac{1}{4}$ to $\frac{1}{8}$ mm fraction was used. This fraction was boiled in dilute hydrochloric acid, to which a small amount of stannous chloride had been added, to remove iron-oxide incrustations. The mineral grains were separated in acetylene tetrabromide and mounted in Aroclor 4465 (n=1.664–1.667). About 500 grains were counted

TABLE 1.—*Generalized section of the geologic formations of Paleocene age and younger in western Tennessee*

System	Series	Group	Formation	Lithology
Quaternary	Recent Pleistocene		Alluvium Loess	Gravel, sand, and silt Silt
	Pliocene(?) (May be early Pleistocene)		Terrace deposits	Sand and gravel
Tertiary			Jackson(?)	Clay, silt, and sand
	Eocene	Claiborne Wilcox		Sand and some clay Clay, sand, and carbonaceous material
	Paleocene	Midway		Clay, sand, marl, and limestone

TABLE 2.—*Composite for all heavy-mineral counts*

Mineral	Sample and percentage																					
	1C	2C	3C	4C	5C	6C	7C	1W	2W	3W	4W	1T	2T	1M	2M	3M	4M	1PTR	2PTR	3PTR	1PMR	2PMR	1RM
Ilmenite	24	26	13	31	35	29	26	35	27	39	24	32	38	4	4	13	28	59	5	20	14	27	4
Zircon	23	4		7	18	12	37	3	17	12	29	13	32	7	4	24	25	12	9	15	11	6	2
Garnet	12	7	4	8	4	p	1	p	p	p		p	p	11	15	p	p		p	p	p	p	30
Tourmaline	11	10	16	19	9	7	10	13	6	3	7	1	p	3	4	4	3	1	1	1	1	6	1
Magnetite	7	1	2	5	1	2	2		5	1	p		1	33	28	19	9	1	50	21	24	35	26
Staurolite	7	16	19	12	10	16	10	10	10	9	12	13	7	18	20	7	13	3	7	10	11	6	1
Rutile	5	4	p	1	3	6	3	2	5	3	7	5	6	p	2	6	3	1	4	6	3	1	p
Leucoxene	4	3	1	4	10	11	5	18	6	3	14	2	2		p	7	4	2	1	1	8	10	2
Kyanite	3	25	44	11	11	17	6	16	24	29	6	26	11	21	21	15	14	15	23	24	27	4	p
Hematite	2	3																	p			4	2
Sillimanite	1	1	1	1	1	p		2	p	1		7		1	p		p	1	p	1	1		p
Fibrolite	p	p		p		p							p										
Zoisite	p	p																					p
Epidote	p										p	p		p	p		p	p		p	p		1
Sphene	p								p		p				p	p	p						
Chloritoid	p	p	p	p		p		p										p					
Xenotime	p												p										
Muscovite		p					p				p					2		4	p	1			
Andalusite		p																					
Monazite		p	p			p		p		1		1	3	p	p	1	1			p		1	p
Corundum		p						p															
Clinozoisite		p										p											
Spinel		p																					
Anatase		p																					
Dumortierite										p													
Glauconite														1									
Biotite																p							p
Hornblende																		p					26
Augite																							2
Hypersthene																							1

p = present, but less than 1 percent.

from each sample. The minerals pyrite, marcasite, and limonite were excluded from the count.

Letter designations following the sample numbers refer to the stratigraphic units from which the samples were taken: "C," Claiborne, "W," Wilcox, "T," Terrace sand, "M," Midway, "PTR," Pliocene(?) terrace deposits of the Tennessee River, "PMR," Pliocene(?) terrace deposits of the Mississippi River, and "RM," Recent deposits of the Mississippi River. The mineral counts are given in the table at the end of the paper.

HEAVY MINERALS FROM SANDS OF THE CLAIBORNE GROUP

Sample 1C was taken from a well in south Memphis, Tennessee, that was bucketed and not drilled with the rotary drill.

Sample 2C is a composite of 240 samples of sand from the depths 250 to 1000 feet in 5 test wells drilled in south Memphis, Tennessee.

The heavy minerals of sample 3C were separated from well cuttings of the same well from which sample 1C was derived and from the same stratigraphic horizon although from a greater depth. Heavy minerals were counted from only the $\frac{1}{2}$ to $\frac{1}{4}$ mm fraction. This sample was not treated with hydrochloric acid.

The heavy minerals of sample 4C were counted from the $\frac{1}{4}$–$\frac{1}{8}$ mm fraction of sample 3C. This sample was not treated with hydrochloric acid.

Sample 5C is a composite sample of sand of the Claiborne group between the depths of 700 and 1000 feet in a test well in south Memphis, Tennessee.

The heavy minerals of sample 6C are from a composite sample of sand of the Claiborne group between the depths of 119 and 619 feet in a test well at Braden, Tennessee, 35 miles northeast of Memphis.

The heavy minerals of sample 7C are from sands of very fine grain size between the depths of 313 and 319 feet in a test well at Braden, Tennessee, 35 miles northeast of Memphis.

HEAVY MINERALS FROM SANDS OF THE WILCOX GROUP

Sample 1W is from the depths 1200 to 1400 feet of a test well at Memphis, Tennessee.

The heavy minerals of sample 2W are from a composite sample of sands of the Wilcox between the depths of 953 and 1054 feet from a test well at Braden, Tennessee, 35 miles northeast of Memphis. It was unsieved but was treated with stannous chloride and water.

Sample 3W was collected from sands in a roadcut of State Highway 57 near Saulsbury, Hardeman County, Tennessee, and is believed to be of Wilcox age. It was not sieved but was treated with stannous chloride and water.

Sample 4W was collected from an outcrop of fine to very fine kaolinitic sand of the Wilcox north of Paris, Tennessee.

HEAVY MINERALS FROM SANDS OF THE MIDWAY GROUP

Sample 1M was collected from sands of the Midway group about 1 mile south of Doyle's store in the bottom of Cub Creek, Hardeman County, Tennessee.

Sample 2M is from sands just above a ledge rock at the same locality as 1M.

Sample 3M was collected from sands stratigraphically below the exposures from which samples 1M and 2M were collected, and just south of Spring Hill, Henderson County, Tennessee.

Sample 4M was collected from sands near the base of the Midway north of Masseyville and about half a mile west of the gravel road to Cave Springs, Chester County, Tennessee.

HEAVY MINERALS FROM TERRACE SANDS OF PLEISTOCENE AGE OR OLDER

Sample 1T was collected from terrace sands of Pleistocene age or older exposed in a roadcut along State Highway 100 near Chickasaw State Park, Chester County, Tennessee.

Sample 2T is from terrace sands of Pleistocene age or older from a roadcut along State Highway 57, just west of the Southern Railway-State Highway 57

overpass, in Hardeman County, Tennessee.

The heavy minerals of sample 1PTR were separated from terrace sands of Pleistocene or Pliocene(?) age exposed on the banks of the Tennessee River along State Highway 129 about half a mile north of Little River, Knox County, Tennessee.

The heavy minerals of sample 2PTR were separated from Pliocene(?) terrace deposits of the Tennessee River near Pittsburg Landing, Hardin County, Tennessee.

The heavy minerals of sample 3PTR came from Pliocene(?) terrace deposits of the Tennessee River 5.8 miles southwest of the river along Highway 79, Henry County, Tennessee.

The heavy minerals of sample 1PMR came from Pliocene(?) terrace deposits of the Mississippi River 5 miles north of Memphis.

The heavy minerals of sample 2PMR were separated from Pliocene(?) terrace deposits of the Mississippi River 4 miles south of Memphis.

In the Pliocene(?) deposits of the Tennessee and Mississippi Rivers, a very rare, green isotropic mineral is consistently present, but this was the only isotropic mineral noted in these sands. There are apparently no consistent differences between heavy-mineral suites from these sands of Pliocene(?) age and heavy-mineral suites from the sands of Eocene age in the subsurface, except that pink and colorless garnet is more common in the Claiborne than in the Wilcox in the subsurface at Memphis.

HEAVY MINERALS FROM SANDS OF RECENT AGE

The heavy minerals of sample 1RM were separated from Recent alluvium of the Mississippi River at Memphis.

The heavy-mineral suite from Recent alluvium of the Mississippi River differs greatly from the heavy-mineral suite characteristic of the sands of Eocene age of western Tennessee and from that of the Pliocene(?) deposits of the Tennessee and Mississippi Rivers.

CONCLUSION

Although it was not the intention of the writer to make any statistical analyses of the occurrence of heavy minerals in the various grade sizes of sands, the count of heavy minerals from the grade sizes seemed necessary for samples from the subsurface because of the manner of collection of these samples. The samples suggest that there is a consistent, although slight, difference between the heavy minerals from sands of the subsurface Claiborne and the heavy minerals from sands of the subsurface Wilcox at Memphis in that garnet occurs more commonly in the Claiborne than in the Wilcox. All other differences may be due to accidents of sorting.

There does not appear to be any significant difference between the heavy minerals of the Wilcox and Claiborne in samples from the well at Braden, Tennessee, 35 miles northeast of Memphis. The heavy minerals from sands of Pleistocene(?) age or older that crop out in Hardeman and Chester Counties, Tennessee, resemble the heavy minerals from both the Wilcox and Claiborne of the subsurface except that garnet is practically absent. Two samples of sands from the Midway contain much garnet which suggests that some of these sands were brought into the area from the north.

Heavy-mineral suites characteristic of the Pliocene(?) and Pleistocene deposits of the Tennessee River resemble the heavy-mineral suites of the Pliocene(?) deposits of the Mississippi River and the older Eocene sands. Heavy-mineral suites from Recent alluvium of the Mississippi River differ from heavy-mineral suites of the older deposits in Tennessee.

Ockerman (1930), in his tables, shows garnet as the most abundant heavy mineral in the Madison and Jordan sandstones of Wisconsin. Although both colorless and pink garnet were observed,

the colorless garnet was far more abundant. Total garnet in heavy-mineral concentrates from 47 samples of the Madison sandstone ranges from 78 to 97 percent, averaging 93 percent. Total garnet in heavy-mineral concentrates from 47 samples of the Jordan sandstone ranges from 40 to 95 percent, averaging 76 percent. Ockerman lists garnet as constituting less than 1 percent of heavy-mineral concentrates from the St. Lawrence formation. The average of garnet in heavy-mineral concentrates from the Madison and Jordan sandstones is 84 percent. However, according to Ockerman (1930), staurolite, kyanite, and anatase "occur so rarely as to be of no significance."

Ockerman does not suggest a source area for the heavy minerals. He states that "the small variety of heavy minerals and the predominance of the stable ones in the Madison and Jordan sandstones are indicative of either a very remote source or the re-working of a pre-existing sedimentary formation, the latter seeming more probable."

Graham (1930) states that heavy minerals in the Cambrian sandstones of Minnesota are "very erratic in their development and of little significance in correlation." However, his histograms show garnet as generally abundant. Heavy minerals in 10 samples of the Franconia sandstone contain 0 to 59 percent of garnet but average 21 percent. Heavy minerals in 35 samples of the Jordan sandstone contain 5 to 90 percent of garnet and average 55 percent. Heavy minerals in 5 samples of the Dresbach sandstone contain 10 to 89 percent of garnet and average 39 percent. Heavy minerals in 4 samples of the St. Lawrence formation contain 25 to 70 percent of garnet and average 50 percent. The average content of garnet in heavy-mineral concentrates from samples from the 4 formations is 41 percent. Graham believed it was "much more probable that the erosion of older sediments supplied most of the sands."

Grim (1936), lists garnet as very rare or missing in samples of both the Claiborne and Wilcox in Mississippi. He suggests (p. 207) that the source area for both the Claiborne and Wilcox must be the same and may have been the "complex of ancient rocks located in the present Piedmont Plateau."

In a recent report on Choctaw County, Alabama, by Toulmin and others (1951), garnet in heavy-mineral suites is listed generally as rare or lacking in the Naheola formation of the Midway group, the Nanfalia formation, the Tuscahoma sand, the Bashi marl member and the rest of the Hatchetigbee formation of the Wilcox group, and the Meridian sand member of the Tallahatta formation of the Claiborne group.

There appears to be a similarity in the heavy-mineral suites in the Claiborne and Wilcox of Mississippi, the Wilcox of Tennessee, the eastern up-dip portion of the Claiborne of Tennessee, and the terrace sands of the Tennessee River. In the depths of the embayment under Memphis, however, the greater percentage of garnet in the Claiborne may suggest a progressive mixing with detrital materials from the north.

The similarity between the heavy-mineral suites of the Pliocene(?) and Pleistocene deposits of the Tennessee River and the Pliocene(?) deposits of the Mississippi (or ancestral Ohio) River suggests that the Pliocene(?) terrace sands and gravels of the Mississippi River were not transported to the area by a river system that drained the Wisconsin and Minnesota areas. Rather, these gravels and sands may have come from areas drained by the Tennessee River.

During Pliocene time the Teays River drained the Piedmont area in part; the ancestral Ohio, White, and Cumberland Rivers could have furnished much of the chert that is a prominent constituent of the Pliocene(?) terrace deposits of the Mississippi River. But if, during Pliocene time, the Teays River drained into

the ancestral Mississippi River, some detrital materials may have come from the Wisconsin-Minnesota area, which would have contributed much pink and colorless garnet; also, the Teays River probably did not drain into the ancestral Ohio River.

The ancestral Ohio, White, and Cumberland Rivers, on the other hand, drained areas underlain partly by Paleozoic limestones and shales and partly by the Paleozoic (Pennsylvanian) sandstones. Thus, it is possible that the Pliocene(?) deposits of the Mississippi River may have originated in the watersheds of the ancestral Ohio, White, and Cumberland Rivers. However, a wide area near the Tennessee River in the northern part of western Tennessee and in western Kentucky is underlain by surficial deposits of chert and quartzite gravels and sands that are similar lithologically to the Pliocene(?) deposits of the Mississippi River. Thus, there is evidence, other than the heavy-mineral suites, that the Pliocene(?) chert- and quartzite-bearing gravelly sand deposits of the Mississippi River originated in the Tennessee River watershed.

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FIGS. 1–4, DECEMBER, 1956

CLAY MINERAL COMPOSITION OF RECENT SEDIMENTS FROM SIGSBEE DEEP

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ABSTRACT

Six cores from the Sigsbee deep in the Western Gulf of Mexico were obtained from the Lamont Geological Observatory for mineralogical studies. Two cores came from a low seaknoll that rises approximately 200 fathoms above the bottom of the deep. Two other cores are from the edge of the seaknoll, and the remaining 2 cores are from the abyssal plain surrounding the seaknoll. The cores from the abyssal plain are characterized by a series of graded layers of silt and clay, whereas those on the seaknoll do not show grading.

Mineralogically these cores contain variable proportions of quartz, calcite, montmorillonite, illite, chlorite, and possibly a minor amount of kaolinite. Montmorillonite is the most abundant clay mineral present, which was unexpected because previous knowledge of the clay minerals in marine sediments indicated that illite and chlorite are the dominant clay minerals in a marine environment. The presence of large quantities of montmorillonite in the abyssal sediments may indicate that much of the montmorillonite carried into the Gulf of Mexico by rivers is not deposited on the continental shelf, but is held in suspension and deposited in deep and quiet water far from shore. Previous reports indicate that the shallow shelf areas are characterized by the presence of illite and chlorite. In general the illite and chlorite in the cores are better developed in sediments that lie below the present surface, even at a depth of a few centimeters, indicating that some crystal structure reorganization has taken place during diagenesis.

INTRODUCTION

The object of this paper is to present the results of some mineral analyses from a suite of sediments collected on the floor of the Gulf of Mexico in the Sigsbee Deep. Samples from cores in the Gulf of Mexico, collected by staff members of the Lamont Geological Observatory and Woods Hole Oceanographic Institution were obtained for study. Six of these cores from the Sigsbee Deep are the basis of this paper (fig. 1).

Four cores used in this study came from the abyssal plain and 2 cores came from a low seaknoll rising about 200 fathoms above the bottom of the deep (fig. 2). Ericson[1] has described the lithology of these cores as follows:

"Typically these cores consist of an upper layer of foraminiferal lutite containing recent species of foraminifera overlying a series of graded layers of dark gray lutite and silt with few foraminifera. The graded bedding of the lower section indicates deposition by an almost continuous series of turbidity currents."

Concerning the cores from the top of the seaknoll Ericson says:

"It is significant that these contain no graded layers of dark gray lutite and silt being in this respect quite unlike the seventy other cores from the abyssal plain and Sigsbee Deep. They afford in this way excellent evidence that the graded layers of the deep cores have been indeed deposited by turbidity currents which have been guided by local topography."

Because of the differences in lithologies between the cores from the abyssal plain and on the seaknoll, it was felt that a study of the mineralogy might prove significant.

[1] Mimeographed descriptions of core lithologies on open file at the Lamont Geological Observatory.

METHOD OF STUDY

The cores, stored at the Lamont Geological Observatory in plastic covered

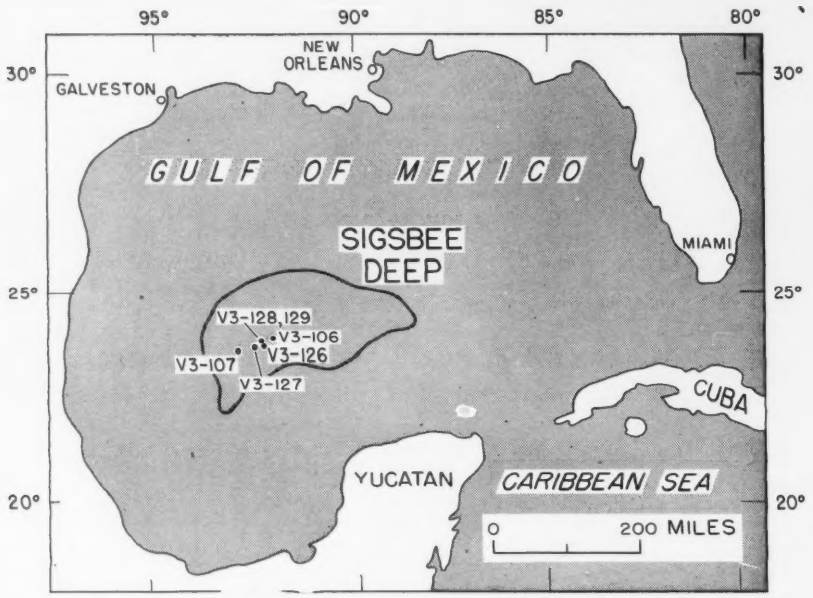

FIG. 1.—Map showing location of cores in Sigsbee Deep.

troughs, had air dried completely when the samples were taken for this study. The procedure used in the preparation and storage of the cores has been described by Ericson (1953). The cores were sampled at every change in color, texture, or lithology.

X-ray diffractometer traces were taken of the powdered untreated samples and oriented slides were prepared of the less than 2 micron fraction. Diffractometer traces were made of the less than 2 micron fraction without treatment, with ethylene glycol treatment, and after heating to 200° C and 475° C. A General Electric XRD-3D spectrogoniometer using nickel-filtered copper radiation was used in the X-ray identifications. Differential thermal analysis curves were made of a selected number of samples but no significant results were obtained because of the diversity of the clay minerals present and their poor crystallinity.

CLAY MINERAL IDENTIFICATION

The samples studied contain variable proportions of quartz, calcite, dolomite, montmorillonite, illite, and chlorite. A small amount of kaolinite may be present in a few samples but its presence is questionable. The argillaceous materials in the cores are almost exclusively 2:1 layer types. The identification of each clay mineral species is possible because of differences in c-axis periodicities which result from variations in composition of the interlayer material and population of the interlayer positions. Illite type clay minerals, designated by capital I on the figures, were identified on the basis of a 10 Å periodicity which did not change with ethylene glycol treatment (fig. 3). Montmorillonite, designated by the letter M, was identified on the basis of a dominant 15.2 to 16 Å basal spacing which expanded to 17 to 18 Å after treatment with ethylene glycol and collapsed

to about 10 Å on heating to 200° C. Chlorite, designated by C on the figures, was identified on the basis of an integral series of orders related to a 14 Å periodicity which are unaltered by glycolation or heating to 200° C. Bradley (1954) has shown that it is very difficult to distinguish chlorite from kaolinite, because kaolinite and chlorite have two characteristic basal reflections in common, at 7 Å and 3.5 Å. Because the 14 Å reflection is masked in these samples by the broad diffuse montmorillonite reflection and mixed layer reflection (ML), the slides were heated to 475° C destroying the reflections at 7 Å and 3.5 Å and increasing the intensity of the reflection at 14 Å which is characteristic of chlorite.

DISCUSSION OF RESULTS

In general, the relative proportions of the clay mineral components were similar in the samples from both the abyssal plain and the seaknoll. Montmorillonite is the dominant clay mineral present in all the cores examined in this study (fig. 4). Using the method described by Johns, Grim, and Bradley (1954), the montmorillonite content was found to be approximately twice that of chlorite and illite which were present in about equal proportions. Kaolinite may be present in small or trace amounts in some samples.

The abundance of montmorillonite over illite and chlorite in the abyssal deep was somewhat surprising because the loss of montmorillonite in near shore marine environments is well established based on several investigations including the work by Dietz (1941); Grim, Dietz and Bradley (1949); Millot (1949); and Grim and Johns (1954). Grim and Johns (1954) have shown that the Guadalupe river sediments in the Rockport area of Texas are characterized by a dominance of montmorillonite but that the bay areas in the vicinity are dominated by illite and chlorite. Montmorillonite content increases as the continental shelf is crossed as Shepard and Moore (1955) have recently pointed out. There are

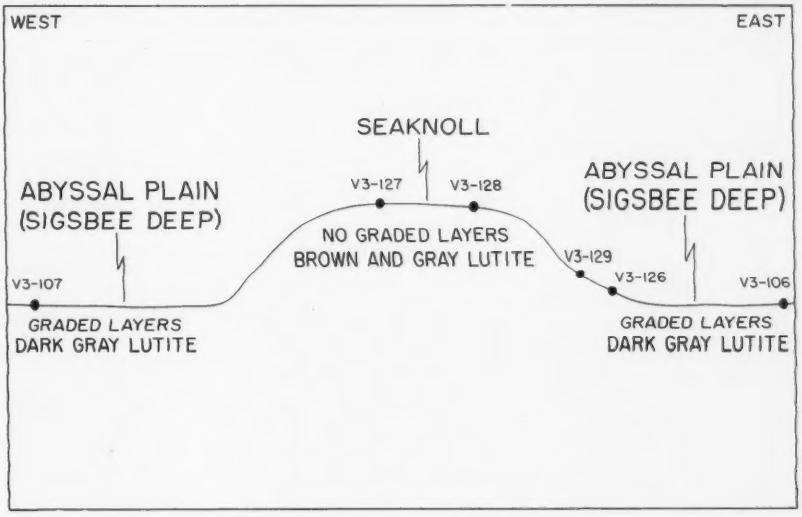

FIG. 2.—Diagrammatic profile of seaknoll.

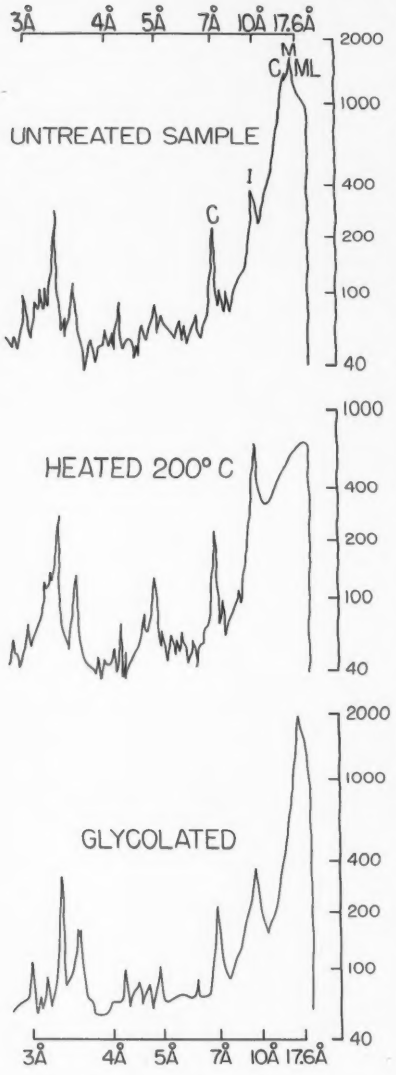

FIG. 3.—Smoothed X-ray spectrometer traces showing an untreated sample and the same sample heated and glycolated.

several hypotheses to explain the presence of abundant *montmorillonite* in the Sigsbee Deep.

Three of the most probable explanations are:

1.—Montmorillonite may be preferentially held in suspension and carried far from shore. This may be due to the small particle size of montmorillonite or to preferential flocculation of the illite and chlorite.

2.—Diagenesis and/or depth factors may have caused the different 2:1 layer clay minerals to form preferentially in certain areas.

3.—Different source areas may supply materials of different compositions and this could be the reason for the clay mineral differences.

Montmorillonite occurs only in extremely small particle sizes (Grim, 1953). Illite and chlorite generally show a larger particle size distribution. On the basis of settling velocities alone, montmorillonite would stay in suspension longer and thus could be carried further from shore. However, other factors such as differential flocculation by ions in marine waters could account for the distribution of the clay minerals. As mentioned above, montmorillonite is the dominant clay mineral in some of the river sediments being carried into the Gulf of Mexico. Recent studies have shown that the near shore areas in the Gulf of Mexico are characterized by a dominance of illite and chlorite relative to other clay minerals (Grim and Johns, 1954). The presence of abundant montmorillonite in the Sigsbee Deep suggests that further studies should be made of the distribution of clay minerals from the near shore regions out into the abyssal deep in order to substantiate the hypothesis of differential flocculation or settling.

Diagenesis and/or depth functions could explain the differences in the clay mineral composition of the near shore areas and the abyssal deep. Grim and Johns (1954) have suggested that montmorillonite changes to illite and chlorite

in the near shore areas as a diagenetic process by the exchange of magnesium and potassium ions for calcium ions. Because of the abundance of montmorillonite in the river waters, an equilibrium may be set up involving magnesium, potassium, and calcium ions leaving a certain amount of montmorillonite in suspension which could be carried to deeper water where it would be deposited. Some of the expandable clay carried into the Gulf is undoubtedly a stripped or degraded 2:1 type of structure and any material that bypassed the near shore area and did not pick up K^+ could, during diagenesis in the deep portions, pick up Ca^{++} or perhaps Na^+ and thus be a diagenetic montmorillonite. Another possibility is that at depth ions other than K^+ and Mg^{++} would be picked up by the stripped lattice and form montmorillonite.

The differences in clay mineral composition in the Gulf of Mexico could be explained by variation in composition in the source areas but enough evidence has been accumulated to show that this hypothesis probably does not account for the differences that exist as shown by this study.

At and near the top of each core the clay minerals illite and chlorite gave X-ray patterns which indicate extremely poor crystal development. At a depth of a few centimeters the illite and chlorite reflections become much sharper and better resolved indicating better interlayer organization. The authors interpret this to mean that the interlayer materials become better organized with slight diagenesis. Studies of cores from the Atlantic ocean show a similar characteristic (Murray and Sayyab, 1955).

X-ray diffractometer patterns of the untreated powdered samples showed some mineralogical differences between the samples from the abyssal plain and the top of the seaknoll. In the abyssal

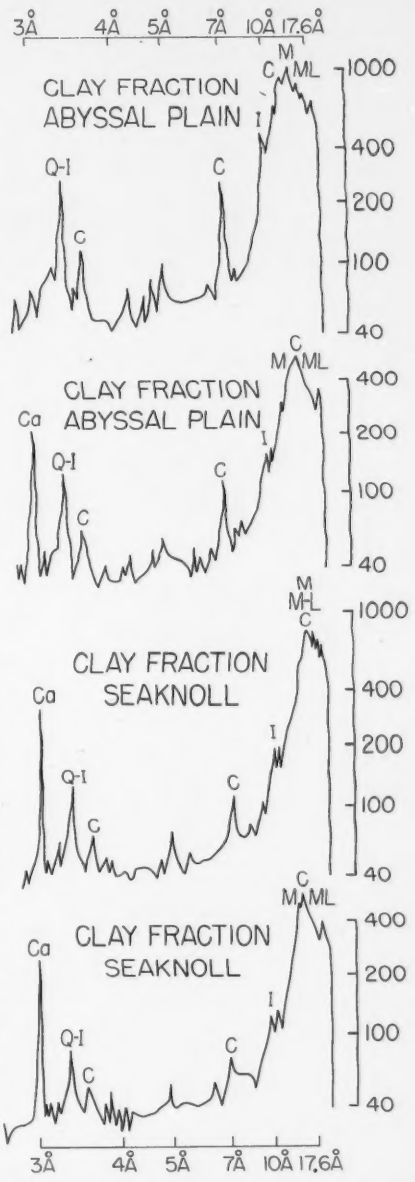

FIG. 4.—Smoothed X-ray spectrometer traces showing abundance of montmorillonite.

plain samples calcite was more abundant than quartz at the top of the cores and at a depth of 100 cm the calcite content decreased markedly with respect to the quartz. This might possibly be caused by a change in physical and chemical conditions related to the end of Pleistocene glaciation. On the seaknoll calcite content was variable with respect to the quartz content at all depths. This may further substantiate the idea that the abyssal plain cycles were deposited by turbidity currents which did not affect the sediments on the seaknoll (Ericson, see footnote page 363).

SUMMARY

A consideration of the results discussed above leads to the following generalizations:

1.—No significant differences in the clay minerals were noted between the sediments on the seaknoll and those from the abyssal plain.

2.—Montmorillonite is the dominant clay mineral component in the Sigsbee Deep. Its presence can best be explained by differential suspension and flocculation or possibly by changes in the interlayer composition caused by slight diagenesis of the newly deposited 2:1 layer clay minerals. Further work on additional samples will have to be done before a definite interpretation can be proposed

3.—Diagenesis affects the crystal perfection of illite and chlorite.

ACKNOWLEDGMENTS

The authors wish to thank Dr. David B. Ericson, Dr. Maurice Ewing, Dr. Bruce Heezen, and Mr. Sam Gerard of the Lamont Geological Observatory for their cooperation in making the cores available for sampling. Appreciation is expressed to the graduate school at Indiana University for providing necessary funds for the procurement of the samples.

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DISCUSSION

FUCOIDAL MARKINGS IN THE SWAN PEAK FORMATION, SOUTHEASTERN IDAHO

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The recent analysis by Coulter (1955) of possible explanations for the conspicuous ridge-like bedding-plane features associated with quartzitic layers of the Swan Peak formation of Ordovician age in southeastern Idaho stimulated a more careful examination of two excellent outcrops of the Swan Peak in Logan and Green canyons, respectively east and northeast of Logan, Utah. Coulter's findings did not seem to agree, in all repects, with the earlier and more casual observations of the writer.

These ridge-like structures are found mostly in thin quartzitic layers separated by fissile shale although they also extend upward as ridges on the tops of quartzitic beds without an intervening shale layer. They are abundant near the contacts of shale and overlying quartzite. The intertwining, described by Coulter, distinctly arises as a result of superposition and intersection.

It seems evident to the writer that the ridges in question were formed before consolidation of the sandy layers as a consequence of local thickening under load. The thin quartzitic layers have thickened, upward and to a lesser extent downward, into ridge-like features due to lateral migration of quartz grains and a few fossil fragments. In cases involving ridges which extend upward from thicker layers of quartzitic sandstone, the internal bedding of the source layer may be completely disrupted and flat fossil fragments variously oriented. Original laminations which have been broken and deformed in certain examples preclude the possibility that fossils were associated with these structures. The explanation here suggested was not considered by Coulter and represents an effect of which variants occur at other stratigraphic horizons in the Paleozoic section of northeastern Utah and southeastern Idaho.

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ERRATA

A NEW METHOD OF EXPRESSING PARTICLE SPHERICITY

BERT C. ASCHENBRENNER, 1956, Jour. Sedimentary Petrology, 26, pp. 15–31

It has been found that the numerical data on Woodbine sandstone contain an error, so that this part of the paper, although still being representative of the method as such, is not numerically representative of Woodbine sandstone. Rectified numerical data may be obtained from the author.

Furthermore, it has been found that the appendix contains the following omissions and misprints:

1) Page 29, left column, 10th line from the bottom: F is the elliptic integral of the first kind and E is the elliptic integral of the second kind. See also page 22, left column, where it says . . . elliptic integrals of the first and second *order* . . . instead of *kind*.
2) Page 29, left column, 4th line from the bottom: Factor b^2 is missing; the formula should read

$$S_E=2\pi b^2\left\{p^2+\frac{1}{q\sin\gamma}\left[\sin^2\gamma E(\gamma, K)+\cos^2\gamma F(\gamma, K)\right]\right\}.$$

3) Page 29, right column, 2nd line from the top: Factor b^3 is missing; the formula should read

$$V_E=\frac{4}{3}\pi abc=\frac{4}{3}\pi\frac{p}{q}b^3.$$

4) Page 29, right column, 4th line from the top: Factor b is missing; it should read . . . The radius of the sphere of equal volume is $b\sqrt[3]{p/q}$.
5) Page 29, right column, 6th line from the top: Factor b^2 is missing; the formula should read

$$S_S=4\pi\left(\frac{p}{q}\right)^{2/3}b^2.$$

6) Page 29, right column, 10th line from the top: Factor π is missing in the denominator; the formula should read

$$\psi'_E=\frac{S_S}{S_E}=\frac{4\pi\left(\frac{p}{q}\right)^{2/3}}{2\pi\left\{p^3+\frac{1}{q\sin\gamma}\left[\sin^2\gamma E(\gamma, K)+\cos^2\gamma F(\gamma, K)\right]\right\}}.$$

Journal of Sedimentary Petrology

INDEX TO VOLUME 26

Abelson, P. H., abstract by..... 184
Aberdeen, E., cited.....144, 146, 155
Acanthocladia guadalupensis Girty, A possible algal-bryozoan symbiot, abstract..... 192
Ackermann, E., cited..... 138
A comparison of two methods for converting grain counts to weight percent composition..... 222
A faunule of unusual nonmarine ostracoda from the Pliocene of Idaho, abstract..... 191
Agassiz, A., cited..... 305
Agnew, A. R., cited.....284, 286
A hand auger for boring Recent sediments..... 162
Alice in graywackeland, abstract..... 188
Allen, J. E., cited.....307, 312
Allen, J. E., note by..... 160
Allison, L. E., cited.....233, 238
A manual piston coring device for use in shallow water..... 64
Amblypneustes spp...... 234
An application of the theory of sediment transport by turbidity currents to the dredging of navigable channels. 119
Antarctica, Sediment distribution in the southern oceans around..... 301
Anderson, C. F., cited.....245, 248, 249, 252
Anderson, N. R., abstract by..... 191
Anderson, R. C., cited.....328, 329, 337
Anderson, R. L., cited.....327, 337
A new method of expressing particle sphericity..... 15
A new method of expressing particle sphericity, errata..... 370
An intraformational conglomerate by mixed sedimentation in the Upper Cretaceous of the Roc-de-Chère, autochthonous chains of High Savoy, France..... 253
Anthraconaia lenisulcata.....343, 349
Anthraconauta sp...... 343
Apfel, E. T., cited.....324, 325
Application of the theory of sediment transport by turbidity currents to the dredging of navigable channels, An..... 119
Arenicola carbonaria..... 352
Arenicolites..... 352
A restudy of the Mohnian-Delmontian contact near Calabasas, California, abstract..... 208
Aschenbrenner, B. C., article by..... 15
Aschenbrenner, B. C., cited.....16, 30
Aschenbrenner, B. C., errata by..... 370
A simple turbidimeter..... 61
A use of roundness to determine depositional environments..... 49
A volumeter for measuring porosity of incoherent sands..... 276
Axenfeld, S., cited.....315, 321

Bachman, G. O., cited.....307, 312
Baker, A. A., cited.....316, 321
Baker, C. L., cited.....258, 267
Baker, F. E., cited.....158, 159
Bancroft, T. A., cited.....328, 337
Bandy, O. L., cited..... 109
Barker, A. C., cited..... 305
Barnes, V. E., cited.....291, 292, 300
Bartlet, M. S., cited.....327, 337
Bather, F. A., cited.....352, 355
Bay, H. X., cited..... 67
Beachrock, Examples of probable lithified..... 307
Beal, M. A., article by..... 49
Beales, F. W., cited.....34, 41
Bell, H. S., cited.....119, 123
Bennett, C. A., cited.....328, 334, 337
Bennett, H., cited.....235, 239
Bergen, F. W., Jr., abstract by..... 208
Binney, E. W., cited.....352, 355
Birse, D. J., cited.....33, 41
Blackman, B., cited.....120, 123
Black, M., cited.....6, 13, 35, 41
Black, T. A., cited.....235, 239
Blankenship, R. R., article by..... 356
Blaustein, M. K., abstract by..... 189
Bokman, J., cited.....166, 167, 168, 169, 171
Bonham, L. C., abstract by..... 178
Bowman, W. J., cited.....258, 267
Bradley, J. S., article by..... 61
Bradley, W. F., cited.....67, 127, 129, 130, 133, 138, 139, 365, 368
Bragg, W. L., cited.....246, 247, 252
Bridge, J., cited.....291, 292, 300
Brooks, H. K., cited.....266, 267
Brooks, J. E., abstract by..... 190
Brooks, R., cited.....112, 118
Brown, R. S., cited.....316, 321
Brunton, G. D., cited.....262, 267
Buck, A. D., note by..... 67
Buckley, H. E., cited.....247, 252
Buerger, M. J., cited.....243, 252
Bullock, K. C., cited.....316, 321
Bundy, W. M., article by..... 240
Burma, B. H., cited.....322, 337
Butts, C., cited..... 4, 13

Cadigan, R. A., cited.....141, 155
Cailleux, A., cited.....284, 285, 286
Calderwood, K. W., cited.....316, 321
California, A restudy of the Mohnian-Delmontian contact near Calabasas, abstract..... 208

California, Eocene diatom florules of the Kellogg and Sidney shales, Mt. Diablo area, abstract..... 208
California, Lower Cretaceous stratigraphic units of northern, abstract 209
California sandstones, Directional properties of some, abstract..... 178
California, Some Foraminifera from rocks of Eocene age of San Nicolas Island, Ventura County, abstract. 209
California, Upper and Middle Miocene Foraminifera from southeastern part of the Los Angeles basin, abstract..... 208
Cambrian) in the northern Appalachian valley of Virginia, Petrology of the arenaceous beds in the Conococheague formation (late..... 3
Campbell, G., cited.....338, 340, 342
Carbonicola..... 343
Carboniferous of north and central Derbyshire, England, Sedimentary structures in the Upper..... 343
Carozzi, A., abstract by..... 178
Carozzi, A., article by..... 353
Carozzi, A., cited.....253, 257
Carrigy, M. A., article by..... 228
Cayeux, L., cited.....32, 34, 35, 41
Chapman, C. A., review by..... 69
Chapman, F., cited..... 305
Chattanooga of the Eastern Highland Rim, Tennessee, Sandy zones in the 338
Chayes, F., cited.....222, 227
Chester, Illinois, Conodonts from the type, abstract..... 191
Chilingar, G. V., cited..... 160
Clark, D. L., abstract by..... 190
Clark, D. L., article by.....313
Clark, D. L., cited.....316, 317, 320, 321
Clark, L. M., cited.....112, 118
Clark, R. S., cited.....319, 321
Clarke, F. W., cited.....243, 252
Clay minerals from the Röt member of the Triassic near Göttingen, Germany..... 125
Clay mineral composition of Recent sediments from Sigsbee Deep..... 363
Clay mineral composition of Recent sediments from the Mississippi River delta, abstract..... 190
Clays in subgraywackes, Permeability loss from swelling of matrix, abstract..... 189
Clements, T., cited.....284, 286
Cloos, E., cited..... 13
Cochran, W. G., cited.....327, 332, 337
Codonophycus..... 320
Collinson, C., abstract by..... 192
Comey, A. M., cited.....244, 252
Comparison of two methods for converting grain counts to weight percent composition, A..... 222
Composita subtilita..... 46
Composition in sandstone classification, The role of texture and, discussion 166
Composition of rock bodies, Multivariate analysis of mineralogic, lithologic, and chemical..... 322
Conant, L. C., cited.....338, 339, 342
Conditions of life in the sea, abstract.. 183
Conkin, J. E., note by..... 68
Conley, R. F., cited.....249, 251, 252
Connaughton, M. P., cited.....232, 238
Conococheague formation (late Cambrian) in the northern Appalachian valley of Virginia, Petrology of the arenaceous beds in the..... 3
Conodonts from the type Chester, Illinois, abstract..... 191
Conodonts, Upper Devonian substages and their world-wide correlation on the basis of, abstract..... 192
Cooke, C. W., cited.....309, 311, 312
Cooke, E. W., cited..... 109
Cooper, J. R., cited.....348, 355
Corthell, E. L., cited..... 124
Coulter, H. W., cited..... 369
Cox, E. P., cited.....15, 30
Crane, G. W., cited.....313, 321
Cretaceous of the Roc-de-Chère, autochonous chains of High Savoy, France, An intraformational conglomerate by mixed sedimentation in the Upper..... 253
Cretaceous stratigraphic units of northern California, Lower, abstract.... 209
Cross-stratification, Flume experiments on the production of stratification and, abstract..... 177
Curley limestone—an unusual biostrome in central Utah, The,..... 313
Curray, J. R., abstract by..... 177

Dallaville, J. M., cited..... 30
Daly, R. A., cited.....119, 123
Dapples, E. C., cited.....13, 140, 155, 167, 169, 171
Davis, D. H., article by..... 140
Debenham, F., cited..... 305
Dendraster: A problem in echinoid taxonomy, abstract..... 193
Derbyshire, England, Sedimentary structures in the Upper Carboniferous of north and central..... 343
Desch, C. H., cited.....246, 252
Devonian of eastern Nevada, Mottled carbonate rock in the Middle..... 32
Devonian substages and their world-wide correlation on the basis of conodonts, Middle, abstract..... 192
Diatom florules of the Kellogg and Sidney shales, Mt. Diablo area, California, Eocene, abstract..... 208
Diatoms as paleoecological indicators, abstract..... 184
Dickey, P. A., cited.....36, 41
Dictyoclostis sp...... 46
Deitz, R. S., cited.....365, 638

Differential compaction of Pennsylvanian sediments in relation to sand-shale ratios, Jefferson County, Illinois, abstract ... 189
Directional properties of some California sandstones, abstract ... 178
Dixon, W. J., cited ... 217, 221, 281, 283, 326, 337
Dodge, C. F., cited ... 30
Douglas, A. V., cited ... 305
Downs, G. R., abstract by ... 189
Dryden, A. L., Jr., cited ... 225, 227, 272, 275
Dunnington, H. V., cited ... 349, 355

Eastern Interior Basin, Silurian reefs of the northern edge of the, abstract ... 187
Ecological interpretations of the Pliocene and Pleistocene stratigraphy in the Great Plains region, abstract ... 179
Eden, R. A., cited ... 343, 355
Edmundson, R. S., cited ... 13
Ellisor, A. C., cited ... 105, 109
Elias, M. K., abstract by ... 182
Elison, J. H., cited ... 319, 321
Emery, K. O., cited ... 140, 144, 148, 155, 158, 159, 307, 312
England, Sedimentary structures in the Upper Carboniferous of north and central Derbyshire ... 343
Environmental conditions affecting the deposition of beach sands between Virginia and Florida, abstract ... 190
Eocene age on San Nicolas Island, Ventura County, California, Some foraminifera from rocks of, abstract 209
Eocene diatom florules of the Kellogg and Sidney shales, Mt. Diablo area, California, abstract ... 208
Ericson, D. B., cited ... 363, 364, 368
Estimation of percentages in thin sections—consideration of visual psychology ... 140
Estimation of Recent sediment size parameters from a triangular diagram 140
Ewing, M., cited ... 119, 123
Examples of probable lithified beachrock ... 307

Fairbank, N. G., article by ... 268
Fairbridge, R. W., cited ... 228, 238
Fan, P. H., article by ... 258
Farnsworth, M., cited ... 246, 252
Faunule of unusual nonmarine ostracoda from the Pliocene of Idaho, A, abstract ... 191
Fenton, C. L., cited ... 320, 321
Fenton, M. A., cited ... 320, 321
Fisher, D. W., cited ... 33, 41
Fisk, H. N., cited ... 105, 109, 124
Flanagan, F. J., articles by ... 213, 222
Flanagan, F. J., cited ... 222, 227
Fleming, R. H., cited ... 302, 303, 306
Florida, Environmental conditions, affecting the deposition of beach sands between Virginia and, abstract ... 190
Florida Miocene, Paleoecology of the, abstract ... 180
Flume experiments on the production of stratification and cross-stratification, abstract ... 177
Folk, R. L., cited ... 160, 166, 167, 168, 169, 171
Folk, R. L., discussion by ... 166
Foraminiferal populations along the central Texas coast, Significance of, abstract ... 180
Foraminiferal zonations in the Tertiary sequence of southwestern Washington, abstract ... 207
Foraminifera from Illinois, Specific variations among arenaceous, abstract. 192
Foraminifera from rocks of Eocene age on San Nicolas Island, Ventura County, California, Some, abstract 209
Foraminifera of Santa Cruz basin, abstract ... 207
Forman, M. J., abstract by ... 185
France, An intraformational conglomerate by mixed sedimentation in the Upper Cretaceous of the Roc-de-Chère, autochthonous chains of High Savoy ... 253
Franklin, N. L., cited ... 328, 334, 337
Frear, G. L., cited ... 244, 252
Frye, J. C., abstracts by ... 179, 186
Frye, J. C., cited ... 152, 154, 155
Füchtbauer, H., cited ... 137, 138
Fucoidal markings in The Swan Peak formation, southeastern Idaho ... 369
Funafuti drill cores and its bearing on the physicochemistry of dolomite, The mineralogy of the, abstract ... 185

Gableman, J. W., cited ... 165
Galliher, E. W., cited ... 233, 238
Garst, J., cited ... 109
Gastrioceras subcrenatum ... 343
Geike, A., cited ... 290, 300
Gilluly, J., cited ... 315, 321
Ginsburg, R. N., cited ... 317, 311, 312
Ginsburg, R. N., note by ... 64
Globigerina ... 255
Globotruncana ... 253, 255, 256
Goldman, M. I., cited ... 43, 48, 246, 248, 252
Goodman, N. R., cited ... 246, 252
Gould, H. R., cited ... 119, 123, 140, 155
Grabau, A. W., cited ... 289, 300
Graham, W. A. P., cited ... 361, 362
Grain orientation studies of Recent sands, abstract ... 177
Grain-size analysis of Jacksonian sediments of Mississippi and adjacent areas ... 103
Granuliferella ... 317
Graphic aids in study of strata ... 42
Gray, H. H., cited ... 290, 291, 292, 293, 300
Great Basin, Triassic in the eastern, abstract ... 191

Great Plains region, Ecological interpretations of the Pliocene and Pleistocene stratigraphy in the, abstract. 179
Greensmith, J. T., article by. 343
Griffin, R. H., cited. 33, 41
Griffiths, J. C., cited. 52, 60, 279, 283
Griggs, D., cited. 242, 252
Grim, R. E., abstract by. 190
Grim, R. E., cited. 67, 109, 126, 127, 138, 139, 266, 267, 361, 362, 365, 366, 367, 368
Grout, F. F., cited. 222, 227
Grove, A., cited. 284, 285, 286
Grover, N. C., cited. 119, 123
Guilcher, A., cited. 284, 285, 286
Gulf of Mexico, Methods and preliminary results in a study of minerals from the eastern. 268
Gulf of Mexico, Shelfedge calcareous prominences in the northeastern, abstract. 186
Gumbel, V., cited. 305

Hadding, A., cited. 349, 355
Hagerman, T. H., cited. 15, 30
Hahn, D. A., cited. 244, 252
Hamilton, G. H., abstract by. 189
Hand auger for boring Recent sediments, A. 162
Hanna, M. A., cited. 64, 66
Hardy, C. T., discussion by. 369
Harrison, J. L., article by. 363
Harting, P., cited. 112, 118
Hatch, F. H., cited. 6, 13, 35, 41
Heavy-mineral assemblages of the coral-reef limestones at the base of the Trichinopoly Cretaceous (Cenomanian to Danian), South India, abstract. 186
Heavy-mineral suites in unconsolidated Paleocene and younger sands, western Tennessee. 356
Hedgpeth, J. W., abstract by. 183
Heezen, B. C., cited. 119, 123
Hewitt, D. F., cited. 34, 41, 43, 48
Hickam, R., note by. 165
Hill, E. S., cited. 320, 321
Hoffman, F. H., cited. 313, 316, 319, 321
Honeyborne, D. B., cited. 126, 139
Hough, J. L., article by. 301
Hough, J. L., cited. 123, 124, 144, 155, 303, 304, 305
Hough, J. L., discussion by. 123
Howard, C. S., cited. 119, 123
Huddle, J. W., cited. 56, 60
Hudson, R. G. S., cited. 349, 355
Huffmann, H., cited. 137, 139
Huitt, J. L., cited. 16, 30
Hunt, J. M., cited. 36, 41

Idaho, A faunule of unusual nonmarine ostracoda from the Pliocene of, abstract. 191
Idaho, Fucoidal markings in the Swan Peak formation, southeastern. 369
Identification of ostracode genera and species in thin sections, The, abstract. 191
Illing, L. V., cited. 111, 118, 307, 311, 312
Illinois, Conodonts from the type Chester, abstract. 191
Illinois, Differential compaction of Pennsylvanian sediments in relation to sand-shale ratios, Jefferson County, abstract. 189
Illinois, Specific variations among arenaceous Silurian foraminifera from, abstract. 192
Indiana, Petrology of gypsum-anhydrite deposits in southwestern. 240
Ingram, R. L., cited. 290, 291, 292, 293, 294, 300
Inman, D. L., cited. 141, 155
Inoceramus. 255
Intraformational conglomerate by mixed sedimentation in the Upper Cretaceous of the Roc-de-Chère, autochthonous chains of High Savoy, France, An. 253
Israelsky, M. C., abstract by. 209

Jacksonian sediments of Mississippi and adjacent areas, Grain-size analysis of. 103
Jasmund, K., cited. 125, 126, 137, 139
Johns, K. H., cited 312, 321
Johns, W. D., Jr., abstract by. 190
Johns, W. D., Jr., cited. 67, 127, 139, 365, 366, 368
Johnson, D. W., cited. 60
Johnson, J. H., cited. 320, 321
Johnson, M. W., cited. 302, 303, 306
Johnston, J., cited. 244, 252
Jones, D. J., abstract by. 191
Jones, S. M., cited. 307, 312
Jordan, G. F., cited. 273, 274, 275

Kanaya, T., abstract by. 208
Kansas and adjacent states, Petrography and genesis of the Ogallala "algal limestone" in, abstract. 186
Kay, M., cited. 258, 263, 267
Kellagher, R. C., articles by. 213, 222
Kellagher, R. C., cited. 222, 227
Kelley, V. C., article by. 289
Kelley, V. C., cited. 291, 292, 294, 300, 307, 312
Kellogg and Sidney shales, Mt. Diablo area, California, Eocene diatom florules of the, abstract. 208
Kelly, K. K., cited. 245, 248, 249, 252
Killebrew, E. B., cited. 339, 342
Kirk, L., cited. 284, 286
Klepser, H. J., cited. 338, 339, 342
Kline, W. D., cited. 244, 252
Koch, H. L., cited. 215, 221
Kolb, C. R., cited. 124
Koritnig, S. 137, 139
Krumbein, W. C., article by. 322

Krumbein, W. C., cited.....13, 15, 16, 18, 20, 30, 43, 48, 50, 56, 60, 61, 63, 109, 140, 141, 144, 146, 155, 167, 169, 171, 213, 221, 232, 236, 238, 258, 261, 263, 268, 270, 271, 275, 280, 281, 283, 290, 300, 332, 337
Krynine, P. D., abstracts by.....184, 186
Krynine, P. D., cited.....3, 5, 6, 14, 166, 167, 171, 261, 267
Kuenen, Ph. H., cited..119, 120, 123, 307, 312
Kullenberg, B., cited.....64, 66
Kummel, B., abstract by..... 183

Ladd, H. S., abstract by..... 183
LaMoreaux, P. E., cited.....361, 362
Lanphere, C. R., cited.....361, 362
Leininger, R. K., cited.....249, 251, 252
Lengyl, E., cited.....112, 118
Leonard, A. B., abstracts by.....179, 186
Leonard, A. G., cited.....33, 41
Levinson, S. A., abstract by..... 190
Linck, G., cited.....111, 118
Lindgren, W., cited.....313, 321
Lippmann, F., article by..... 125
Lippmann, F., cited.....125, 126, 137, 139
Lloyd, R. M., note by..... 64
Lohman, K. E., abstract by..... 184
Los Angeles Basin, California, Upper and Middle Miocene foraminifera from southeastern part of the, abstract..... 208
Lonsdale, J. T., cited..... 267
Lotze, F., cited.....125, 139
Loughlin, G. F., cited.....313, 321
Louisiana and Guam, Tertiary reef limestones from southern, abstract.... 185
Lovering, T. S., cited.....313, 321
Lower Cretaceous stratigraphic units of northern California, abstract..... 209
Lower limits to the *So* coefficient..... 158
Ludwick, J. C., abstract by..... 186
Ludwick, J. C., article by..... 276
Ludwick, J. C., cited.....119, 120, 122, 123
Lundahl, A. C., cited.....49, 60
Lytle, M. A., article by..... 111

MacAlpin, A. J., cited..... 312
MacCarthy, G. R., cited.....56, 60
MacClintock, P., cited.....324, 325, 337
MacEwan, D. M. C., cited..... 139
Macnair, P., cited.....353, 355
Maher, S. W., article by..... 338
Mallams, P., cited.....158, 159
Mann, J. F., Jr., note by..... 156
Manual piston coring device for use in shallow water, A..... 64
Marginopora vertebralis..... 236
Marine ecology as an aid in the teaching of invertebrate paleontology and stratigraphy, abstract..... 182
Marine level-bottom animal communities of Recent seas, abstract..... 182
Marr, J. E., cited.....42, 48
Massey, F. J., Jr., cited.....217, 221, 281, 283, 326, 337
Mather, K. F., cited.....338, 342
Mathews, A. A. L., cited.....111, 118
Matthews, W. H., Jr., abstract by..... 182
Mattox, R. B., cited.....49, 60
McAllister, J. F., cited.....34, 41, 284, 286
McFarlan, E., Jr., cited..... 124
McGregor, D. J., cited.....240, 241, 246, 252
McIntire, W. G., note by..... 162
McKee, E. D., abstract by..... 177
McKee, E. D., cited.....33, 41, 290, 291, 292, 293, 294, 297, 300
McKelvey, V. E., cited....291, 292, 293, 300
Mead, W. J., cited.....347, 355
Menard, H. W., cited.....119, 120, 122, 123
Methods and preliminary results in a study of minerals from the eastern Gulf of Mexico..... 268
Middle Paleozoic tectonic history of north-central and northwestern Utah, abstract..... 190
Migliorini, C. I., cited.....119, 120, 123
Miller, R. L., cited.....281, 283, 322, 337
Millot, G., cited.....365, 368
Milner, H. B., cited.....213, 221
Mineral composition of the Yazoo clay by X-ray diffraction methods..... 67
Mineralogy of the Funafuti drill cores and its bearing on the physicochemistry of dolomite, The, abstract... 185
Miocene foraminifera from southeastern part of the Los Angeles basin, California, Upper and Middle, abstract. 208
Miocene, Paleoecology of the Florida, abstract..... 180
Mississippi and adjacent areas, Grain-size analysis of Jacksonian sediments of..... 103
Mississippi River delta, Clay-mineral composition of Recent sediments from the, abstract..... 190
Monaghan, P. H., article by..... 111
Monroe, W. H., cited..... 67
Moore, D. G., cited .54, 57, 58, 59, 60, 365, 368
Moore, R. C., abstract by..... 180
Moret, L., cited.....254, 257
Morgan, J. P., cited.....307, 312
Morgan, J. P., note by..... 162
Mossman, R. C., cited..... 306
Mosteller, F., cited.....332, 337
Mottled carbonate rock in the Middle Devonian of eastern Nevada..... 32
Movement of rocks by wind, The..... 284
Mueller, J. C., abstract by..... 189
Muessing, S. J., cited.....316, 321
Müller, K. J., abstract by..... 192
Multiple-cone sample splitter, The.... 213
Multivariate analysis of mineralogic, lithologic, and chemical composition of rock bodies..... 332
Murphy, M. A., abstract by..... 209
Murray, G. E., cited.....105, 108, 109
Murray, H. H., article by..... 363
Murray, H. H., cited.....367, 368
Murray, J., cited..... 306

National Research Council, cited....103, 109
Neaverson, E., cited..... 306
Nevada, Mottled carbonate rock in the Middle Devonian of eastern..... 32
New method of expressing particle sphericity, A..... 15
New method of expressing particle sphericity, A, errata..... 370
New Mexico, Transitional Permo-Pennsylvanian sediments of the Rowemora Basin, abstract..... 187
New techniques in paleoecology, abstract..... 184
Nicholas, R. L., article by..... 3
Nolan, J. B., cited.....34, 41
Northrop, S. A., cited..... 312
Nutting, P. G., cited.....279, 283

Ockerman, J. W., cited.....361, 362
Ogallala "algal limestone" in Kansan and adjacent states, Petrography and genesis of the, abstract..... 186
Olson, J. S., cited.....327, 332, 337
Ooliths, The origin of calcareous..... 111
Organic sedimentation in Warnbro Sound, western Australia..... 228
Oriented phenomena produced by sedimentation from turbidity currents and in subaqueous slope deposits, abstract..... 178
Origin of calcareous ooliths, The..... 111
Osmond, J. C., article by..... 32
Osmond, J. C., cited.....32, 36
Ostracoda from the Pliocene of Idaho, A faunule of unusual nonmarine, abstract..... 191
Ostracode genera and species in thin sections, The identification of, abstract 191
Otto, G. H., cited.....42, 48, 213, 215, 221, 289, 300

Paleocene and younger sands, western Tennessee, Heavy-mineral suites in unconsolidated..... 356
Paleoecological evidence from sediments, abstract..... 183
Paleoecological evidence furnished by fossils, abstract..... 183
Paleoecological indicators, Diatoms as, abstract..... 184
Paleoecology of the Florida Miocene, abstract..... 180
Paleoecology, New techniques, in, abstract..... 184
Paleoecology symposium, abstracts of 182–184
Paleozoic tectonic history of north-central and northwestern Utah, Middle, abstract..... 190
Parejas, E., cited.....253, 257
Parker, F. L., cited.....270, 275
Patnode, H. W., cited.....233, 238, 239
Payne, T. G., cited.....290, 291, 292, 300
Penetrants, Recent and ancient, abstract..... 182
Pennsylvanian sediments in relation to sand-shale ratios, Jefferson County, Illinois, Differential compaction of, abstract..... 189
Pentland, A., cited.....15, 30
Permeability loss from swelling of matrix clays in subgraywackes, abstract... 189
Perma-Pennsylvanian sediments of the Rowemora Basin, New Mexico, Transitional, abstract..... 187
Peronella leserui..... 234
Peterson, D. O., cited.....316, 319, 320, 321
Petrographic analysis of a stratigraphic type oil field in west central Texas, abstract..... 189
"Petrographic Mineralogy," review of.. 69
Petrography and genesis of the Ogallala "algal limestone" in Kansas and adjacent states, abstract..... 186
Petrology of gypsum-anhydrite deposits in southwestern Indiana..... 240
Petrology of the arenaceous beds in the Conococheague formation (late Cambrian) in the northern Appalachian valley of Virginia..... 3
Pettijohn, F. J., cited.....6, 13, 14, 22, 30, 43, 48, 49, 51, 60, 61, 63, 109, 140, 155, 158, 159, 166, 167, 213, 221, 246, 250, 252, 261, 267, 270, 271, 275, 280, 283, 290, 300, 330, 331, 332, 337, 340, 341, 342, 348, 355
Philippi, E., cited.....302, 304, 306, 308
Phleger, F. B., abstract by..... 180
Phleger, F. B., cited.....119, 123, 270, 275
Pinsak, A. P., cited.....240, 252
Pirie, J. H. H., cited..... 306
Plastic spray in laboratory and field... 68
Platystrophia.....341, 342
P. ponderosa..... 340
Playford, P. E., cited.....230, 238
Plectogyra tumula..... 317
Pleistocene stratigraphy in the Great Plains region, Ecological interpretations of the Pliocene and, abstract..... 179
Pliocene and Pleistocene stratigraphy in the Great Plains region, Ecological interpretations of the, abstract.... 179
Pliocene of Idaho, A faunule of unusual nonmarine ostracoda from the, abstract..... 191
Plumley, W. J., article by..... 140
Pohl, E. R., cited..... 338
Popov, V. I., cited.....249, 252
Posidonia spp.....230, 236
Posnjak, E., cited.....251, 252
Potter, P. E., Cited.....299, 300, 327, 332, 333, 337
Powers, M. C., cited.....50, 60
Powers, S., cited.....266, 267
Pratje, O., cited..... 306
Preparation of thin sections of well cuttings, The..... 165
Price, W. A., cited.....122, 123

Problem of scientific nomenclature applicable to fragmentary fossils, abstract. . . . 180
Proctor, P. D., article by. . . . 313
Proctor, P. D., cited. . . . 313, 316, 321
Prouty, C. E., cited. . . . 3, 4, 12, 14
Puri, H. S., abstract by. . . . 180
Puri, H. S., cited. . . . 311, 312

Quiring, von Heinrich, cited. . . . 111, 118

Ramberg, H., cited. . . . 242, 248, 252
Rao, C. G., abstract by. . . . 186
Rastall, R. H., cited. . . . 6, 13, 35, 41
Rau, W. W., abstract by. . . . 207
Raup, D. M., abstract by. . . . 193
Recent and ancient penetrants, abstract 182
Recent sands, Grain orientation studies of, abstract. . . . 177
Recent seas, Marine level-bottom animal communities of, abstract. . . . 182
Recent sediments, A hand auger for boring. . . . 162
Recent sediments from Sigsbee Deep, Clay mineral composition of. . . . 363
Recent sediments from the Mississippi River delta, Clay-mineral composition of, abstract. . . . 190
Recent sediment size parameters from a triangular diagram, Estimation of. 140
Renard, A. F., cited. . . . 306
Renzetti, B. L., cited. . . . 315, 321
Resig, J., abstract by. . . . 207
Restudy of the Mohnian-Delmontian contact near Calabasas, California, abstract. . . . 208
Rexroad, C. B., abstract by. . . . 191
Rich, J. L., cited. . . . 307, 312, 338, 342
Richardson, E. G., cited. . . . 61, 63
Rigby, J. K., abstract by. . . . 192
Rigby, J. K., cited. . . . 313, 316, 319
Riley, N. A., cited. . . . 49, 60
Rittenhouse, G., cited. . . . 232, 238
Rochford, D. J., cited. . . . 234, 238
Roe, J. S., cited. . . . 230, 238
Rogers, C. P., Jr., cited. . . . 312
Role of texture and composition in sandstone classification, The, discussion. 166
Rosenfeld, M. A., cited. . . . 52, 60, 274, 283
Rothpletz, A., cited. . . . 111, 118
Röt member of the Triassic near Göttingen, Germany, Clay minerals from the. . . . 125
Roundness to determine depositional environments, A use of. . . . 49
Rowemora Basin, New Mexico, Transitional Permo-Pennsylvanian sediments of the, abstract. . . . 187
Rowland, R. A., cited. . . . 126, 138
Rubey, W. W., cited. . . . 290, 300, 341, 342
Rusnak, G. A., abstract by. . . . 177
Russell, R. D., cited. . . . 31, 49, 60

Safford, J. M., cited. . . . 339, 342
Sample splitter, The multiple-cone. . . . 213
Sanders, J. E., abstract by. . . . 178
Sand-grain orientation and geological application, abstract. . . . 177
Sandstone classification, The role of texture and composition in, discussion. . . . 166
Sandy zones in the Chattanooga of the Eastern Highland Rim, Tennessee. 338
Sangree, J. B., Jr., abstract by. . . . 187
Santa Cruz Basin, Foraminifera of, abstract. . . . 207
Sargent, R., cited. . . . 315, 321
Sayyab, A., cited. . . . 367, 368
Schlanger, S. O., abstract by. . . . 185
Schmalz, R. F., abstract by. . . . 185
Schollenberger, C. J., cited. . . . 233, 238
Schott, G., cited. . . . 302, 306
Schott, W., cited. . . . 302, 304, 306
Schumm, S., discussion by. . . . 284
Schwade, I. T., cited. . . . 36, 41
Schwalb, H., abstract by. . . . 192
Scientific nomenclature applicable to fragmentary fossils, Problem of, abstract. . . . 180
Sedimentary reflections of the depositional environment in a coastal lagoon, abstract. . . . 181
Sedimentary structures in the Upper Carboniferous of north and central Derbyshire, England. . . . 343
Sediment distribution in the southern oceans around Antarctica. . . . 301
Shaw, D. B., article by. . . . 258
Sharp, R. P., cited. . . . 34, 39, 41
Shelfedge calcareous prominences in the northeastern Gulf of Mexico, abstract. . . . 186
Shelton, J. S., cited. . . . 284, 286
Shepard, F. P., article by. . . . 49
Shepard, F. P., cited. 54, 57, 58, 59, 60, 103, 105, 109, 119, 120, 123, 141, 155, 365, 368
Shirley, J., cited. . . . 349, 355
Shrock, R. R., cited. 14, 290, 300, 348, 352, 355
Sidney shales, Mt. Diablo area, California, Eocene diatom florules of the Kellogg and, abstract. . . . 208
Sidwell, R., abstract by. . . . 187
Siever, R., cited. . . . 299, 300, 332, 333, 337
Significance of living foraminiferal populations along the central Texas coast, abstract. . . . 180
Sigsbee Deep, Clay mineral composition of Recent sediments from. . . . 363
Silurian foraminifera from Illinois, Specific variations among arenaceous, abstract. . . . 192
Silurian reefs of the northern edge of the Eastern Interior Basin, abstract. . . 187
Silver, C., cited. . . . 291, 292, 294, 300
Simple turbidimeter, A. . . . 61
Sirrine, G. K., cited. . . . 316, 319, 320, 321
Slack, H. A., cited. . . . 332, 337

Sloss, L. L., cited.....30, 140, 155, 167, 169, 171, 258, 263, 267, 290, 300
Smith, C. L., cited.....111, 118
Smith, J. F., cited.....119, 123
Smith, P., abstract by..... 208
Smith, W. C., cited..... 305
Snedecor, G. W., cited.....324, 326, 337
Society of Economic Paleontologists and Mineralogists
Abstracts of Pacific Coast Section meeting..... 207
Announcements..... 73
Annual business meeting..... 193
Membership list..... 74
Program and abstracts of 30th annual meeting..... 176
Program for Chicago meeting..... 70
Records and activities..... 172
So coefficient, Lower limits to the..... 158
Soil boulders in the Temecula arkose.... 156
Some foraminifera from rocks of Eocene age on San Nicolas Island, Ventura County, California, abstract..... 209
Sorby, H. C., cited.....31, 50, 60
Southard, J. C., cited.....245, 248, 249, 252
Sparks, P. W., cited.....284, 285, 286
Specific variations among arenaceous Silurian foraminifera from Illinois, abstract..... 192
Sphericity, A new method of expressing particle..... 15
Stanley, G. M., cited.....284, 286
Stanton, R. L., cited..... 238
Stather, J. W., cited.....352, 355
Stephen, I., cited..... 139
Stetson, H. C., cited...119, 123, 270, 275, 306
Stewart, F., cited.....36, 41
Stewart, F. H., cited.....250, 252
Stewart, H. B., Jr., abstract by..... 181
Stille, H., cited.....125, 139
Stokes, W. L., abstract by..... 190
Stow, M. H., cited..... 14
Stratification and cross-stratification, Flume experiments on the production of, abstract..... 179
Strickland, J. W., cited.....43, 48
Strøm, K. M., cited.....233, 238
Subgraywackes, Permeability loss from swelling of matrix clays in, abstract..... 189
Sun, Ming-Shan, article by..... 103
Sun, Ming-Shan, cited.....105, 109
Sullwold, H. H., cited..... 312
Sverdrup, H. U., cited.....302, 303, 306
Swan Peak formation, southeastern Idaho, Fucoidal markings in the... 369
Swartz, F. M., cited.....12, 14
Swineford, A., abstract by..... 186
Swineford, A., cited.....6, 14, 152, 154, 155
Sylvester-Bradley, P. C., abstract by... 180

Taber, S., cited.....248, 252
Taggart, A. F., cited.....213, 221
Tanner, W. F., articles by.....158, 307
Tanner, W. F., cited.....158, 159, 311, 312
Taylor, H., cited.....244, 252
Taylor, R. E., cited..... 31
Temecula arkose, Soil boulders in the.. 156
Tennessee, Heavy-mineral suites in unconsolidated Paleocene and younger sands, western..... 356
Tennessee, Sandy zones in the Chattanooga of the Eastern Highland Rim..... 338
Terry, R. D., cited..... 160
Tertiary reef limestones from southern Louisiana and Guam, abstract.... 185
Tertiary sequence of southwestern Washington, Foraminiferal zonations in the, abstract..... 207
Tesnus formation of trans-Pecos Texas, The..... 258
Tesnusocaris goldichi..... 266
Texas coast, Significance of living foraminiferal populations along the central, abstract..... 180
Texas, Petrologic analysis of a stratigraphic type oil field in west central, abstract..... 189
Texas, The Tesnus formation of trans-Pecos..... 258
Texture and composition in sandstone classification, discussion, The role of..... 166
The Curley limestone—an unusual biostrome in central Utah..... 313
The identification of ostracode genera and species in thin sections, abstract..... 191
The mineralogy of the Funafuti drill cores and its bearing on the physico-chemistry of dolomite, abstract... 185
The movement of rocks by wind..... 284
The multiple-cone sample splitter..... 213
The origin of calcareous ooliths..... 111
The preparation of thin sections of well cuttings..... 165
The role of texture and composition in sandstone classification, discussion. 166
The Tesnus formation of trans-Pecos Texas..... 258
Thickness of strata..... 289
Thompson, D'Arcy W., cited.....16, 31
Thompson, W. O., cited....289, 300, 341, 342
Thorp, E. M., cited.....111, 118
Thorson, G., abstract by..... 182
Thurston, E. F., cited.....112, 118
Tickell, F. G., cited.....15, 31
Toulmin, L. D., cited.....361, 362
Transitional Permo-Pennsylvanian sediments of the Rowemora Basin, New Mexico, abstract..... 187
Trask, P. D., cited..... .....105, 109, 158, 159, 233, 235, 236, 238
Treadwell, R. C., cited.....307, 312
Triangular diagram, Estimation of Recent sediment size parameters from a..... 140

Triassic in the eastern Great Basin, abstract. . . . 190
Triassic near Göttingen, Germany, Clay minerals from the Röt member of the. . . . 125
Trichinopoly Cretaceous (Cenomanian to Danian), South India, Heavy-mineral assemblages of the coral-reef limestones at the base of the, abstract. . . . 186
Tukey, J. W., article by. . . . 332
Tukey, J. W., cited. . . . 332, 337
Turbidimeter, A simple 61
Turbidity current deposits down the slope of an alpine basin, Tracing, abstract. . . . 178
Turbidity currents and in subaqueous slope deposits, Oriented phenomena produced by sedimentation from, abstract. . . . 178
Turbidity currents to the dredging of navigable channels, An application of the theory of sediment transport by. . . . 119
Turner, F. J., cited. . . . 242, 252
Twenhofel, W. H., cited. . . . 14, 158, 159, 289, 290, 300
Tyler, S. A., cited. . . . 158, 159

Uniformitarianism is a dangerous doctrine, abstract. . . . 184
Upper and Middle Miocene foraminifera from southeastern part of the Los Angeles Basin, abstract. . . . 208
Upper Devonian substages and their world-wide correlation on the basis of conodonts, abstract. . . . 192
Upson, J. E., cited. . . . 306
Urry, W. D., cited. . . . 304, 306
Use of roundness to determine depositional environment, A. . . . 49
Utah, Middle Paleozoic tectonic history of north-central and northwestern, abstract. . . . 190
Utah, The Curley limestone—an unusual biostrome in central. . . . 313

Van Tuyl, F. M., cited. . . . 32, 41
Vaughan, T. W., cited 111, 118
Verhoogen, J., cited 242, 252
Vernon, R. O., abstract by 180
Virginia and Florida, Environmental conditions affecting the deposition of beach sands between, abstract. . 190
Virginia, Petrology of the arenaceous beds in the Conococheague formation (late Cambrian) in the northern Appalachian valley of. . . . 3
Volumeter for measuring porosity of incoherent sands, A. . . . 276
Vorobiev, A. L., cited. . . . 249, 252

Wadell, H. cited 15, 31, 50, 60
Wagner, W. R., cited. . . . 165
Waksman, S. A., cited 235, 239
Waldschmidt, W. A., cited 9, 14
Walker, G. F., cited 130, 139
Walkley, A., cited. . . . 233, 239
Wallace, R. C., cited 33, 41
Walton, W. R., abstract by. . . . 186
Wanless, H. R., abstract by 189
Warn, G. F., abstract by. . . . 187
Warnbro Sound, western Australia, Organic sedimentation in. . . . 228
Washington, Foraminiferal zonations in the Tertiary sequence of southwestern, abstract. . . . 207
Weaver, C. E., cited. . . . 129, 130, 133, 138
Weir, G. W., cited. . . . 290, 291, 292, 293, 294, 297, 300
Wengerd, S. A., article by. . . . 42
Wengerd, S. A., cited . . . 43, 48, 291, 292, 300
Wentworth, C. K., cited 15, 31, 215, 221, 232, 239
Wilbert, L. J., Jr., cited. . . . 124
Wilgus, W. L., cited 215, 221
Williams, F. E., cited. . . . 313, 321
Wilson, J. L., cited 3, 4, 12, 14
Wimberley, C. S., cited 141, 155
Wiseman, J. D., cited. . . . 235, 239
Wood, A., cited 35, 41

X-ray diffraction methods, Mineral composition of the Yazoo clay by. . . . 67

Yazoo clay by X-ray diffraction methods, Mineral composition of the. . . 67
Youden, W. J., cited. . . . 220, 221

Zingg, T., cited 15, 18, 31

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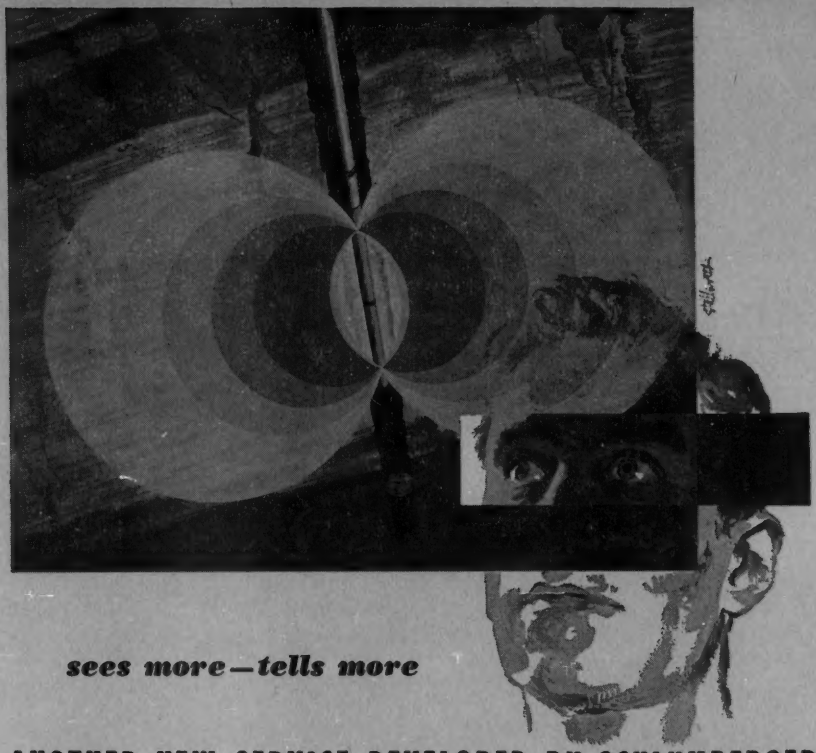

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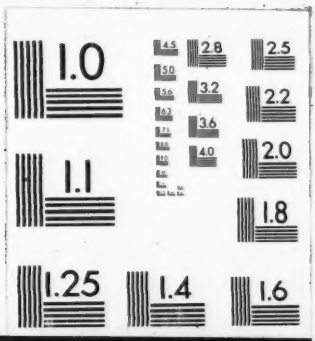
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